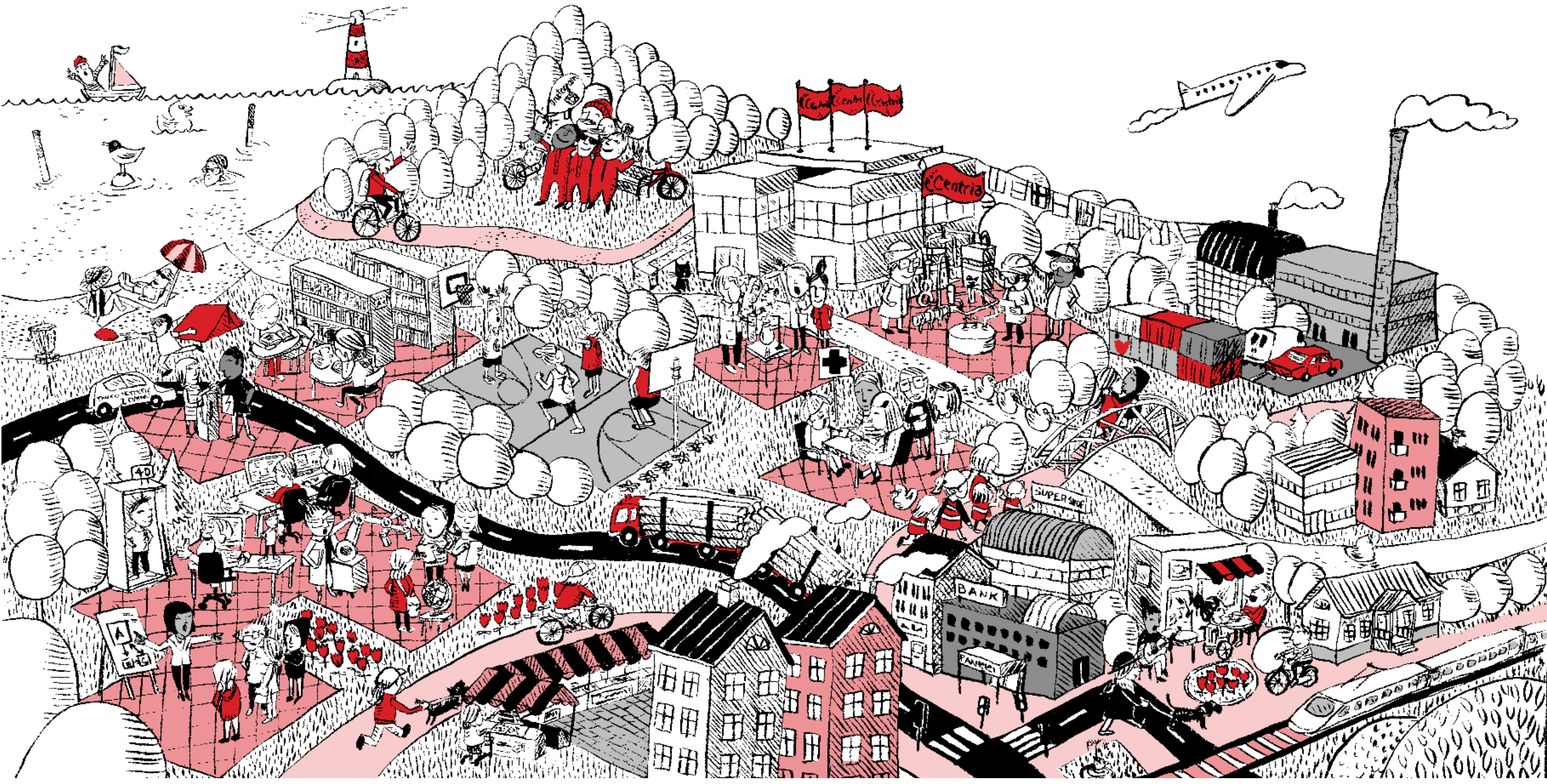
Xinyin Yin

SUSTAINABLE TREATMENT METHODS OF MUNICIPAL SEWAGE SLUDGE

Thesis
CENTRIA UNIVERSITY OF APPLIED SCIENCES
Environmental Chemistry and Technology
March 2022



ABSTRACT

Centria University of Applied Sciences	Date March 2022	Author Xinyin Yin
Degree programme Environmental Chemistry and Technology		
Name of thesis SUSTAINABLE TREATMENT METHODS OF MUNICIPAL SEWAGE SLUDGE		
Centria supervisor Mikko Kuusisto		**Pages** 24+3
Instructor Mikko Kuusisto		

The main purpose of this thesis was to realize sustainable utilization of municipal sewage sludge. Previous sludge disposal methods were introduced, including landfill, incineration, ocean dumping and agricultural land use. Due to the harmful substances in sludge, these methods will harm the environment when used.

Sludge can be used as a substrate to produce hydrogen and biogas. This thesis introduces three methods of hydrogen production: anaerobic fermentation, plasma gasification and supercritical water gasification. Anaerobic digestion is used to produce biogas. These methods can reduce the cost of hydrogen production from sludge and improve the hydrogen production rate. Hydrogen production by anaerobic fermentation has certain requirements for substrates, and sludge needs to be co-fermented with other substrates to maintain the yield. The advantage of plasma gasification is sludge volume reduction, which can reach 41.19 %. The average hydrogen production rate of supercritical water gasification method is the highest when the conditions higher than 374 °C and 22.1 MPa. Supercritical water is used as gasification medium to produce hydrogen.

Key words
Hydrogen production, municipal sewage sludge, sewage

CONCEPT DEFINITIONS

List of abbreviations

TCOD	Total chemical oxygen demand, in milligrams per liter
PG	Plasma gasification
SCW	Supercritical water
SCWG	Supercritical water gasification
WAS	Waste activated sludge
H_2S	Hydrogen sulfide
SAD	Single-stage anaerobic digestion
TAD	Two-stage anaerobic digestion
VFAs	Volatile fatty acids
TVA	Total volatile acid

ABSTRACT
CONCEPT DEFINITIONS
CONTENTS

FIGURES

GRAPHS

TABLES

1 INTRODUCTION

The rapid growth of sludge production is one of the main environmental problems facing humans today. The annual amount of sludge produced by Finnish sewage treatment plants is about 840000 tons, and the annual sludge output is still growing at a rapid rate (Kätkä 2013). Therefore, the disposal of sludge has brought large problems to sewage treatment plants and environmental management departments. With the increasingly strict environmental standardization and people's desire for sustainable utilization is gradually increasing, the sustainable utilization of sludge has become the goal. Therefore, on the premise of realizing sludge harmlessness, energy utilization of sludge should be carried out as far as possible. Turning sludge into energy can not only protect the environment, but also alleviate the lack of energy in the future.

Sludge is a semi-solid slurry and the final product after sewage treatment. The main characteristic of sludge is high water content, and its composition is very complex. It is usually composed of organic matter, inorganic matter, suspended or dissolved particles. Other inorganic impurities are pigments, heavy metals and pathogens. Sludge from different sources has different contents of each component (Kätkä 2013). According to the classification of sewage sources, municipal sewage sludge can be divided into domestic sewage sludge and industrial sewage sludge. Domestic sewage sludge is the sewage sludge discharged from the daily life of residents, dominated by organic matter. It mainly comes from residential buildings and public buildings. Sewage sludge produced in operations or processing activities in different industries is known as industrial sewage sludge, which mainly contains heavy metals, trace organic compounds that are difficult to biodegrade, and potential pathogens such as viruses and bacteria. Therefore, sludge needs to be properly treated before recycling and utilization. (Shankar, R., Kumar, S., Prasad, K. A., Khare, P., Varma, A. & Yadav, V. 2021, 193-216)

The traditional sludge disposal methods are sanitary landfill, incineration, ocean dumping and agricultural land use. Sludge landfill requires a large area of land and may pollute groundwater. Sludge incineration technology is relatively complex and may cause air pollution (Nyyssönen 2015). Dumping sludge into the sea will pollute the water environment, which has been prohibited by international treaties (Hwang, I., Kang, H., Lee, I. & Oh, J. 2012, 888-894). The land use of sludge needs to be implemented according to strict standards, otherwise it will cause more serious soil pollution and affect the health of animals, plants and human beings (Lei 2009). Therefore, the sustainable utilization of sludge has become the center of sludge disposal in the future.

From the perspective of economic development, resource development and utilization and urban ecological environment protection, sustainable utilization is an ideal way out for sludge disposal. There are many methods for sustainable utilization of sludge, such as sludge gardening utilization, sludge composting, production of building materials from sludge, sludge energy utilization. The purpose of this paper is to describe the sludge treatment process and traditional disposal methods, and to introduce how the sludge can be used as energy. This thesis is divided into three parts: the first part introduces the source, treatment process, equipment and traditional treatment process of sewage sludge. The second part introduces the energy utilization of treated sludge, such as the preparation of hydrogen and biogas. The third part is the summary of the current situation of sludge treatments and the future prospect of sustainable utilization of sludge.

2 BASIC KNOWLEDGE OF SEWAGE SLUDGE

Untreated municipal sewage consists of municipal sludge, sludge in sewage pit and septic tank. The sewage treatment process of municipal sewage treatment plant is divided into two parts. One part is the liquid part of sewage. The other part is the solid part of sewage, which is called sludge suspended solid. After the sewage is treated, the residual sludge suspension is sent to the sludge treatment process. (Bhat, S., Cui, G., Li, W., Wei, Y., Li, F., Kumar, S. & Ameen, F. 2021, 259-283)

2.1 Source of sewage sludge

Sewage is transported from the public channel network to the pump station through large pipelines, and rainwater is transported from the storm water tank to the pump station through small pipelines. Untreated sewage from pump station and fecal station is transported to pre-treatment. Figure 1 shows the sewage and sludge treatment process of municipal sewage treatment plant. The washed solid can be collected and separated from water by pre-treatment, also known as mechanical treatment. Mechanical treatment refers to the separation and concentration of various components in sewage, which is used to separate sludge suspended solids. Filtration and sedimentation are two examples of mechanical treatment. In pre-treatment, bar screen is used for screening and filtering to remove coarse particles such as rags, paper, plastics and metals in sewage, so as to prevent damage and blockage of downstream equipment and pipelines. The grit chamber classifies heavy sand to remove grease and gravel. Finally, the remaining solid sludge is extracted by gravity in the sedimentation tank. (Nyyssönen 2015.)

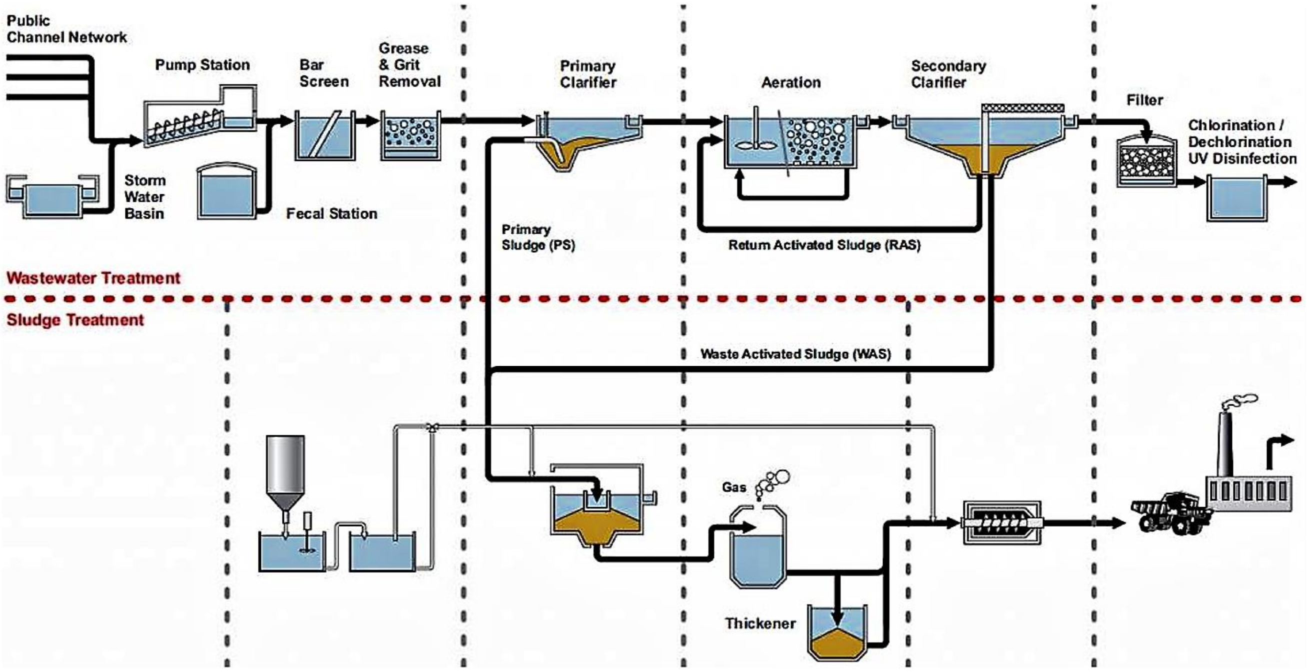


FIGURE 1. Sewage and sludge treatment process (adapted from Tilley, e., ulrich, l., luethi, c., reymond, p. & zurbruegg, c.)

The primary treatment method is also mechanical treatment. After pre-treatment, the sewage is introduced into the primary clarifier for primary treatment. The function of clarifier is to remove solids, produce cleaner sewage and concentrate solids. The solid concentration removed from the sewage reduces the volume of sludge dewatering and disposal. The sludge is transported to the sludge digestion process through pipelines. In the primary treatment, the primary clarifier is used to reduce the water flow rate and precipitate the organic solids to the bottom of the tank. The primary clarifier can reduce the content of suspended solids and pollutants embedded in suspended solids to reduce the organic load on the secondary process. (Nyyssönen 2015.)

The sewage treated in the primary clarifier is transported to the secondary clarifier for biological treatment. Biological treatment is to remove the residual substances in the sewage after primary treatment. In the secondary treatment, sewage suspended solids first flow through the aeration tank. The principle of aeration is to pump air into the pool, which is conducive to the reproduction of specific bacteria, promote the rapid growth of bacteria in sewage and form a population easy to settle. These bacteria eat the organic matter in the suspended matter of sewage and reduce the content of organic matter in sewage. The aerated sewage is transported to the secondary clarifier, the organic matter is condensed and deposited under the action of bacteria, and sludge is formed at the bottom of the secondary clarifier. This sludge is called secondary sludge, also known as biological sludge. The secondary sludge is transported to the sludge digestion process through pipeline. (Jebrail 2016.)

The sewage treated in the secondary clarifier is sent to the tertiary treatment, also known as chemical treatment. Tertiary sludge, also known as chemical sludge, is obtained through chemical precipitation and filtration. Chemicals are added to biological sludge to improve and remove suspended solids in sludge. (Kätkä 2013.)

2.2 Sludge treatment process

A large amount of sediment is stored at the bottom of the primary clarifier and the secondary clarifier. The solid sediment from the primary clarifier is called primary sludge, and the solid sediment from the secondary clarifier is called secondary sludge. Primary sludge contains a lot of organic matter, some microorganisms and pathogens, heavy metals and methane gas. Among them, microorganisms and pathogens can cause harmful effects on the environment, and heavy metals are regarded as harmful by-products. Therefore, it is necessary to properly treat the primary sludge. The purpose of sludge treatment process is to remove harmful substances in sludge and reuse the nutrients in sludge. At the same time, the sludge treatment process reduces the water content of sludge and helps to reduce the cost of subsequent disposal. (Nyyssönen 2015.)

Sludge treatment process is divided into three parts: sludge digestion, sludge concentration and sludge dewatering, which is the core of sludge treatment. Transportation depends on the next step of sludge treatment. (Nyyssönen 2015.)

2.2.1 Sludge digestion

Sludge digestion is the first step of sludge treatment process. The primary sludge and secondary sludge are transported to the digestion room through pipelines for digestion treatment. Sludge digestion can reduce the content of organic and harmful substances in sludge. It can be divided into anaerobic digestion and aerobic digestion, depending on the requirements of the overall cost. Anaerobic digestion is a process of decomposing organic matter by bacteria, which is a long process from at least 12 days to at most

30 days. Bacteria in sludge use heat for digestion to produce methane gas. Methane gas is used as energy for sludge digestion to realize the energy cycle. (Nyyssönen 2015.)

Aerobic digestion is to degrade organic solids in sludge with the help of oxygen and introduce oxygen into the reactor with the help of the blower. Bacteria in sludge convert organic matter into water and carbon dioxide, and ammonia and amino groups into nitrates. Compared with anaerobic digestion, aerobic digestion takes less time, but consumes more energy. (Nyyssönen 2015.)

2.2.2 Sludge thickening

The main purpose of sludge thickening is to increase the solid concentration of sludge and reduce the water content in sludge, so as to reduce the volume of sludge. If the volume of sludge is reduced, the cost of subsequent sludge treatment can be reduced and the efficiency of subsequent treatment can be improved (Kätkä 2013). The sludge concentrator can increase the solid concentration. The common sludge concentrator is dissolved air flotation. Dissolved air flotation produces liquid effluent by dissolving air in sludge under strong pressure and then releasing air at atmospheric pressure in the flotation tank, so that solid and concentrated sludge remain at the bottom. Figure 2 shows the structure of dissolved air flotation. (Hydromo 2021.)

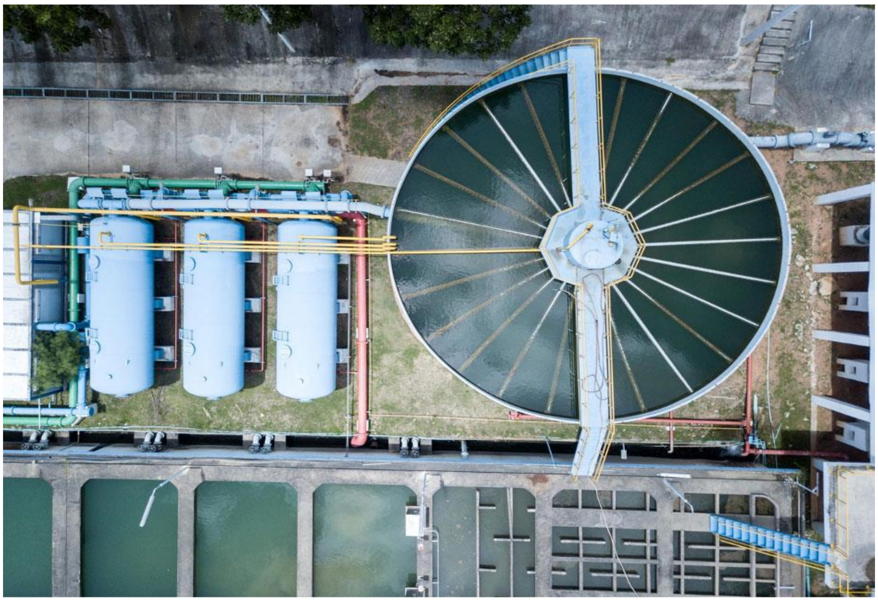


FIGURE 2. The dissolved air flotation system (Hydromo 2021.)

2.2.3 Sludge dewatering

Sludge dewatering is the key and inevitable step of sludge treatment process. Sludge dewatering will remove a large amount of water from the sludge. The dewatered sludge is easier to dispose of and has more economic value. The amount of water that can be removed by sludge dewatering is related to the quality of sludge and water distribution. Different types of water in sludge suspension can be distinguished. The water in the cell is chemically combined, and the free water is not combined with sludge particles, which is usually removed by mechanical dehydration. Surface water adheres to the particle surface, and the capillary force between water conservancy sludge particles is combined in the solid gap. There are many different dehydration methods, such as centrifuges, vacuum filters, filter press and drying beds. (Kätkä 2013.)

2.3 Equipment overview

The dewatering equipment uses vacuum or centrifugal movement to separate the water and solids in the sludge. The specific characteristics depend on the dewatering method. Table 1 shows the comparison of different methods of sludge dewatering. The belt filter press has the shortest process time and drying time, and the centrifuge has the lowest operating cost and capital cost. Therefore, centrifuges and belt filter presses are widely used. (Bhat, S., Cui, G., Li, W., Wei, Y., Li, F., Kumar, S. & Ameen, F. 2021, 259-283)

TABLE 1. Different methods of sludge dewatering (GlobalSpec's Engineering360 1999.)

Type	Cake Dryness % solids	Solids Recovery % solids capture	Process/Drying Time time (measurement)	Operating Cost	Capital Cost	Chemical/ Flocculent Usage
Vacuum filters	16-45*	85-95	Fast (minutes or hours)	High	Moderate	Moderate
Filter presses	40-60	80-95	Very fast (minutes or hours)	High	High	High
Centrifuges	20-35**	85-90	Fast (minutes or hours)	Moderate	Low	High
Drying beds	25-60	90-100	Slow (weeks or months)	Very low	Low	Low

2.3.1 Centrifuges

Sludge dewatering by centrifuge has been widely used in the United States and Europe. The centrifuge uses sedimentation and centrifugal force to separate the solid and liquid in the sludge, as shown in Figure 3. Sludge and polymer coagulant are fed at the inlet of the feed pipe and then transported to the rotating bowl. The spiral vortex is generated inside the rotating drum, and the speed of the drum is slightly higher than that of the vortex, resulting in a speed difference. The liquid is then discharged from the bottom of the drum and the solid is transported to an additional drying stage at the top of the drum (GN Solids Control 2007). The centrifuge has many characteristics, such as convenient maintenance, simple structure and low energy consumption. But it also generates heat, occasional noise and vibration. (Nyyssönen 2015.)

FIGURE 3. Sludge dewatering centrifuge equipment (adapted from GN Solids Control 2007.)

2.3.2 Belt filter press

The belt filter press has two porous belts and many rollers, which rotate continuously and the sludge can be fed continuously, as shown in Figure 4. The energy consumption of belt filter press is lower than that of centrifuge. It is a common dehydration equipment. The sludge and polymer are transported to the mixer through the feed pipe, and then the regulated sludge is transported to the gravity drainage area for concentration. The sludge moves on a belt driven by a roller, which presses the sludge to remove free water, and these liquids are discharged at the bottom of the machine. Finally, a mechanical scraper removes the dry material from the belt (Kätkä 2013). Belt filter press has the advantages of easy maintenance and inspection, low noise and low consumption, but it also has some disadvantages. Open equipment inevitably has smell, needs regular washing and care, and sharp substances will damage the belt. (Kätkä 2013.)

FIGURE 4. The belt pressure filter (Shandong Better Environmental Protection Technology Co. 2006.)

2.3.3 Drying beds

The drying bed consists of perforated drainage pipe and gravel base, as shown in Figure 5. The gravel base is covered with a layer of fine sand, the drainage pipe is laid in the base, and the sludge is placed on the top of the sand layer. The water in the sludge flows to the drainage pipe by gravity or evaporation. Large scale drying usually takes a long time and is affected by weather factors. If the weather is cloudy and wet, the drying time may be up to several months. The speed of drying depends on the amount of sludge, water content and the area of available sand bed (Sautya 2018). The advantages of drying bed are low cost and low energy consumption. The disadvantages are that it has a large demand for space and needs to consider climate factors. (Sautya 2018.)

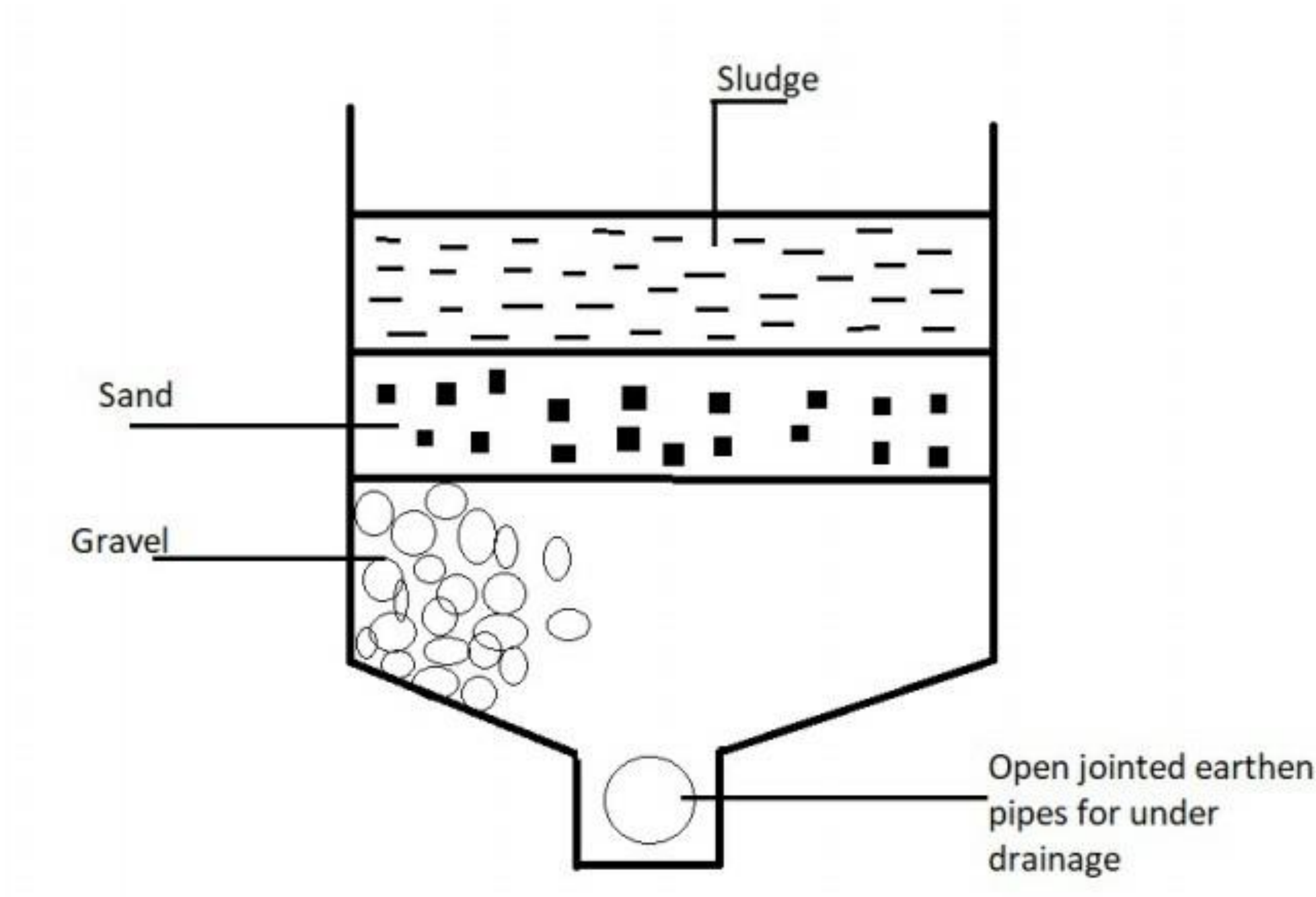


FIGURE 5. Principle of drying bed (Sautya 2018.)

2.4 Sludge disposal process

In the United States, most sludge disposal methods are used in agriculture, followed by incineration and sanitary landfill, and a small part is used for ecological restoration. In Europe, sludge disposal methods are mainly sanitary landfill and land use. In China, sludge disposal methods are mainly incineration and sanitary landfill (Fan 2018). Sanitary landfill, incineration and land use are dominant in the traditional sludge disposal methods, because these three technologies have matured after a long time of development. Sludge dumping into the sea is also a sludge disposal technology, which is similar to incineration and landfill. (Lei 2009.)

2.4.1 Sanitary landfill

Sludge sanitary landfill technology began to be used in the 1960s, and it has the advantages of simplicity and low cost. But there are many problems at the same time. First, sludge landfills occupy a large area of land. Secondly, the water content of dewatered sludge is still very high, which will lead to the formation of leachate and gas. Leachate is a seriously polluted liquid. If the anti-seepage treatment is not done well, it will lead to potential soil pollution and groundwater pollution. Methane, the main gas produced by the landfills, will enter the atmosphere, which may cause explosion and burns. Finally, sludge landfill not only increases the work difficulty of landfill compaction equipment, but also increases the adverse environmental conditions of the landfill. Therefore, more attention needs to be paid to the maintenance and management of landfill. (Lei 2009.)

2.4.2 Sludge incineration

Sludge incineration technology began to be used in the 1930s, which has the advantages of fast speed and high efficiency. The sludge contains a certain amount of organic components. The dewatered and dried sludge is sent to the combustion furnace for heat treatment, which can carbonize all organic matter and minimize the sludge volume. Compared with landfill, incineration does not require so much space. (Lei 2009.)

Dry sludge is required for incineration. Due to its low heat content, some sludge incineration plants use coal or oil as auxiliary fuel to increase heating output. This incineration will produce residues such as smoke and dust, which will cause air pollution. Moreover, heavy metals and other toxic substances in sludge will pollute the atmosphere again with the spread of smoke and dust. On the other hand, the incineration residue is rich in many non-combustible inorganic minerals and some incompletely burned organic residues, which may lead to soil pollution after filling again and indirect secondary pollution of the water body. In addition, the investment in incineration equipment is huge and the treatment cost is high. (Lei 2009.)

2.4.3 Ocean dumping

Putting the treated sludge into the sea through pipeline or transportation is a simple treatment method with low processing cost. In order to ensure seawater dilution and self-purification, the marine disposal area is generally within 10 km from the coast and the depth is about 25 m. However, with the increasing awareness of ecological environment, the possible impact of sludge on marine ecological environment has attracted people's attention. The Chinese government has stipulated that sewage sludge will no longer be disposed of at sea since the 1990s. The EU urban sewage treatment law has prohibited its member states from dumping into the sea since the late 1990s. (Lei 2009.)

2.4.4 Land use

After the EU urban sewage treatment law banned the dumping of sludge into the sea, the land use of sludge has become the best method for sludge disposal approved by European countries. Sludge contains a large amount of organic matter, as well as nitrogen, phosphorus, potassium and other nutrients required for crop growth. Therefore, the land use of sludge has advantages. The rational use of sludge for land not only solves the pollution problem of other fertilizers, but also adds a new organic fertilizer method to the agricultural field. (Lei 2009.)

The treated sludge still contains a small amount of microorganisms, pathogens, heavy metals and other harmful substances. If it is directly used in agriculture, these harmful substances will pollute soil, air and water, and then endanger the health of human beings, animals and plants. Therefore, the land use of sludge needs to be implemented with stricter standards. (Lei 2009.)

3 HYDROGEN PRODUCTION FROM SLUDGE

At present, the most important fuel in the world is fossil fuel. However, when fossil fuels are burned, they will produce greenhouse gases and other pollution. And fossil fuels are non-renewable energy. There is a problem of energy shortage in many countries in the world. Renewable energy has been given top priority. As a renewable energy, hydrogen can solve the problem of energy shortage if the technology is mature. (Dong 2020.)

Hydrogen is a clean energy because it has clean combustion products and only produces water vapor during combustion. It has a lower calorific value of 120 MJ/kg and a higher calorific value of 144 MJ/kg. Hydrogen and fuel cells have been proved to be good energy sources, showing advantages in transportation systems. Although methane is also renewable energy, it will produce greenhouse gases after combustion. (Rivera, I., Schröder, U. & Patil, S. 2019, 871-898)

At present, hydrogen accounts for about 2 % of energy supply. The production cost of hydrogen is higher than that of fossil fuels. Organic matter will produce hydrogen through dark fermentation. Sludge is a common waste in life. Sludge contains a large amount of organic matter. The best treatment method is to use sludge as energy. The conversion of sludge into hydrogen will become a win-win situation. This chapter will introduce the method of hydrogen production from sludge. (Veras, T., Mozer, T. & César, A. 2017, 2018-2033)

3.1 Hydrogen production from anaerobic fermentation sludge

Sludge can produce renewable hydrogen through anaerobic fermentation. Anaerobic fermentation is divided into three stages. First, complex polymers are hydrolyzed into simple organic compounds. The organic compounds are then converted to acids. Finally, acetic acid is produced. In the final step, volatile fatty acids, hydrogen, and carbon dioxide are produced. (Zahedi, S., Sales, D., Romero, L. & Solera, R. 2013, 85-91)

Recent studies have found that hydrogen production using only sludge has low yield and high cost. Because when only sludge is used as the substrate of fermentation, there will be many limitations, such as nutritional imbalance. In Leonor Sillero's study, the co-fermentation of several different substrates was mentioned for the production of hydrogen. This fermentation method can combine the characteristics of different individual substrates to improve the efficiency of hydrogen production. Wine vinasse has a very high content of organic matter and is suitable for co-fermentation with sludge. Their TCOD ranges from 20 to 30 g TCOD/L and pH ranges from 3 to 5. In Leonor Sillero's study, the hydrogen production efficiency was increased by 1.53 times after mixing sludge, wine vinasse and poultry manure. In conclusion, sludge is more suitable for hydrogen production by mixed co-fermentation with other organic wastes. (Sillero, L., Solera, R. & Perez, M. 2022, 3667-3678)

3.2 Hydrogen production from sludge plasma gasification

Plasma gasification (PG) is a good method to treat sludge and produce hydrogen. Figure 6 is a summary of the method of PG hydrogen production (Qi, H., Cui, p., Liu, Z., Xu, Z., Yao, D., Wang, Y., Zhu, Z. & Yang, S. 2021). According to the example of sludge treatment in plasma gasifier in the study of Wang, M., Mao, M., Zhang, M., Wen, G., Yang, Q., Su, B. & Ren, Q. (2019). The carbon conversion rate of gasification sludge was 99.9 %, and the volume reduction rate was 41.19 %. In addition, the energy conversion efficiency of heavy metals in solid products reached 71.8 % and the fixation efficiency was 99 %. In addition, PG has many advantages, such as removing toxic organic compounds. The syngas produced by PG can be used in energy heat recovery and power generation systems to reduce energy consumption. PG can fix heavy metals in inert slag and improve sludge treatment efficiency. (Wang et al. 2019, 29-36)

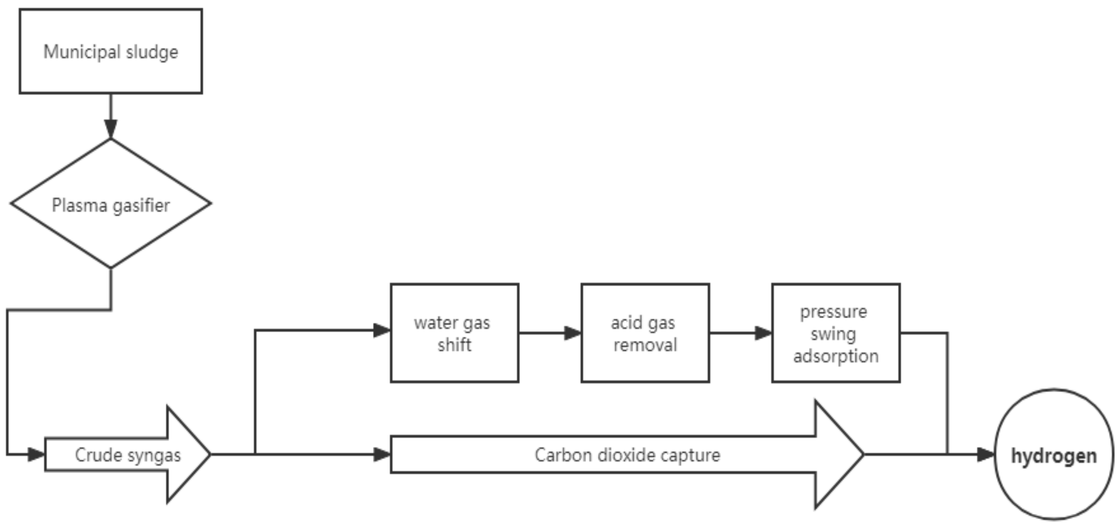


FIGURE 6. Summary of PG hydrogen production (adapted from Qi et al. 2021.)

In the research of Qi et al. (2021), by comparing the plasma gasifier and entrained flow gasifier, it was concluded that the plasma gasifier will produce more CO and H_2. At the same time, the effects of different gasification agents on PG efficiency of municipal solid waste were compared. The results show that the PG efficiency of municipal solid waste is the highest when air is used as gasification agent. The efficiency of using air as gasification agent is 7 % higher than that of using steam as gasification agent.

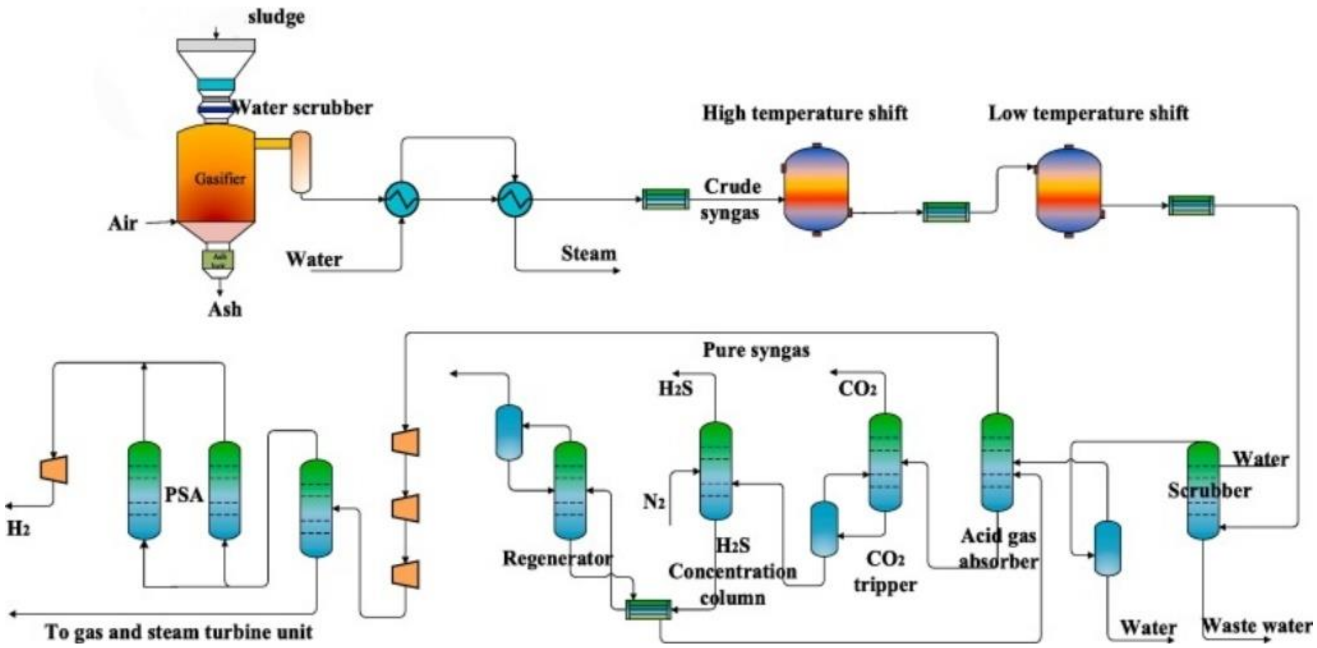


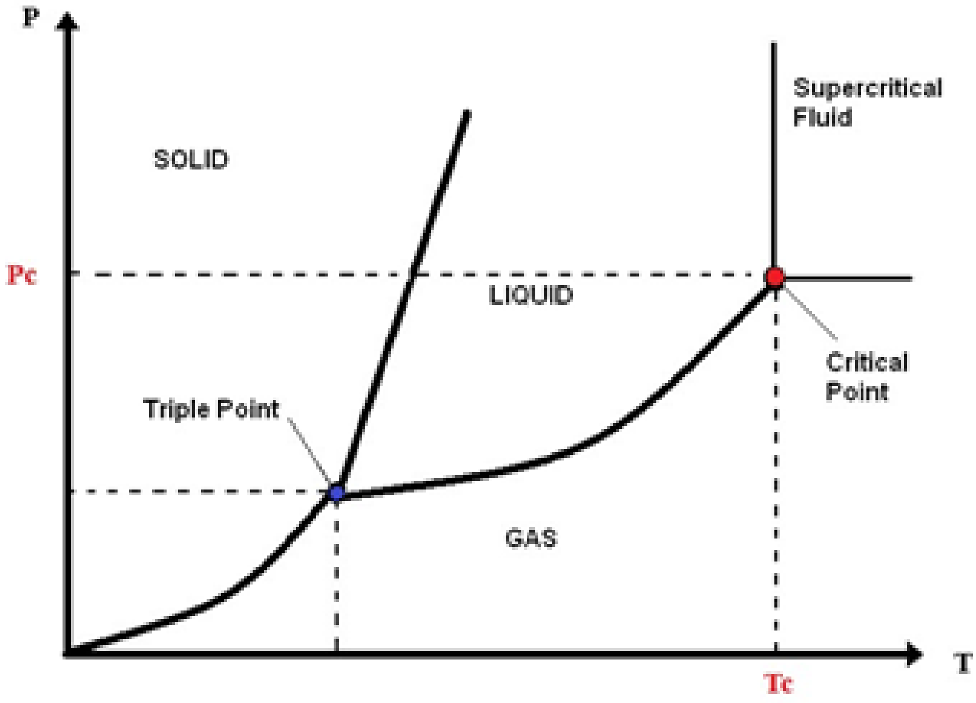
FIGURE 7. The process of municipal sludge to H_2 (Qi et al. 2021.)

As shown in Figure 7, sludge first passes through gasifier and air is used as gasification agent. Because to change the temperature and realize heat recovery, crude syngas needs to pass through the heat exchanger. Then, pure syngas is generated at the top of the back through acid gas absorber. After pressure swing adsorption unit, hydrogen is produced.

3.3 Hydrogen production by SCWG of sludge

Supercritical water means that when the water pressure and temperature reach a specific value, water expands due to high temperature and water vapor is compressed due to high pressure. At this time, the density of water and the density of water vapor are exactly the same. At this time, there is no difference between the liquid and gas of water, and it becomes a fluid with high pressure and high temperature.

The range shown in the graph 1 is supercritical water. Supercritical water has attracted more and more attention because of its low cost, no pollution and good physical properties. (Schmieder, H., Abeln, J., Boukis, N., Dinjus, E., Kruse, A., Kluth, M., Petrich, G., Sadri, E. & Schacht, M. 2000, 145-153)



GRAPH 1. Supercritical Water (Ciuffi 2020.)

Sludge is the main by-product formed in the process of sewage treatment. The main organic components in wastewater sludge are fat, protein and carbohydrate. Wastewater sludge also contains heavy metals, viruses, bacteria and other pathogenic microorganisms. Therefore, conventional treatment methods such as incineration, composting and landfill was hard to solve wastewater sludge. Sludge is a wet biomass with high energy content. Wet biomass and organic waste can be effectively gasified under hydrothermal conditions to produce hydrogen rich fuel gas. However, sludge with high water content must be dried before conventional gasification. Therefore, supercritical water gasification (SCWG) is a suitable method to treat high moisture biomass waste (wastewater sludge). SCWG can reduce costs while producing more gaseous fuels. (Schmieder et al. 2000, 145-153)

SCWG for wastewater sludge treatment can be carried out in different reactors. It is a very complex process to convert wastewater sludge into gas fuel by SCW. Fixed bed batch, tubular and continuous stirred tank reactors can be used as SCWG reactors. In Casademont's research, the reaction of sludge to gas fuel is shown as follows (Casademont, P., García-Jarana, M., Sánchez-Oneto, J., Portela, J. & Ossa, E. 2017, 237-261):

Hydrolysis:

$$C_nH_mO_y+(n-y)H_2O \rightarrow nCO+(n-y+m/2)H_2 \quad (1)$$

Oxidation:

$$H_2+1/2O_2 \rightarrow H_2O \quad (2)$$

$$CO+1/2O_2 \rightarrow CO_2 \quad (3)$$

$$CH_4+2O_2 \rightarrow CO_2+2H_2O \quad (4)$$

Methanation:

for CO:

$$CO+3H_2 \leftrightarrow CH_4+H_2O \quad (5)$$

for CO_2:

$$CO_2+4H_2 \leftrightarrow CH_4+2H_2O \quad (6)$$

Water-gas shift:

$$CO+H_2O \leftrightarrow CO_2+H_2 \quad (7)$$

SCW technology can be divided into three methods. It is classified according to the oxidation coefficient, which is defined as the ratio of the actual amount of air to the theoretical amount, such as supercritical water oxidation ($n \geq 1$), supercritical water gasification ($n = 0$) and supercritical water partial oxidation ($0 < n < 1$). The purpose of supercritical water gasification and supercritical water partial oxidation is to generate hydrogen from wastewater sludge. The purpose of supercritical water partial oxidation is to completely treat the organic matter in wastewater and sludge. (Casademont et al. 2017, 237-261)

Compared with other methods, SCWG method shows higher energy conversion efficiency of wastewater sludge. The table 2 shows the conversion method of wet material energy. (Ibrahim, A.& Akilli, A. 2019, 10328-10349)

TABLE 2. Energy conversion efficiency of different conversion methods (Ibrahim, A.& Akilli, A. 2019, 10328-10349)

Moisture content (%)	**5**	**31**	**55**	**75**
Conversion method	**Energy conversion efficiency (%)**			
Thermal gasification	61	55	47	27
Pyrolysis	57	53	45	27
Liquefaction	39	37	36	34
Anaerobic digestion	31	31	31	31
SCWG	55	55	55	55

It can be seen from Table 2 that SCWG is the conversion method with the best comprehensive conversion rate among the five conversion methods. The conversion of wastewater sludge into hydrogen by SCWG may be an important solution to solve its disposal problem. From another economic point of view, SCWG reduces the cost of sludge disposal. SCWG is carried out at a reaction temperature and pressure higher than SCW (374 °C and 22.1 MPa). Using SCW as the gasification medium to convert biomass with high moisture content such as sludge into hydrogen without the drying process is a promising technology at present. (Ibrahim, A.& Akilli, A. 2019, 10328-10349)

4 BIOGAS PRODUCTION FROM SLUDGE

The increasing demand for energy reflects the importance of renewable energy and increases the pressure on traditional energy. Therefore, bioenergy produced by sludge decomposition helps to eliminate the pressure of traditional energy and solve the problem of energy crisis. Biogas is produced by anaerobic fermentation of sludge. As a renewable energy source, biogas has gradually attracted attention. (Lee, S., Tsang, Y., Lin, K. & Lee, J. 2022.)

Biogas is a renewable clean energy, which is mainly composed of a large amount of methane, carbon dioxide, trace nitrogen and sulfide. In the process of sludge digestion, the organic part of sludge is separated and sent to anaerobic digestion tank. Under anaerobic conditions, organic compounds and various organic waste are biodegraded in the presence of fermentation microorganisms to produce methane rich gas mixture. This process is called biological methanation. Biogas is a mixture of many gases, and its characteristics are similar to natural gas. Biogas can be burned for cooking, drying agricultural and sideline products, lighting, gas welding and heating. It can also be used as chemical raw materials for the production of formalin, methanol and carbon tetrachloride. The feed liquid and sediment discharged after fermentation in the biogas plant contain rich nutrients and can be used as fertilizer and feed. The development of biogas not only provides economic benefits for the society, but also provides a direction for sustainable development. (Lee, S., Tsang, Y., Lin, K. & Lee, J. 2022.)

4.1 Sludge fermentation process

The fermentation process of sludge usually includes sludge collection, pre-treatment, digester, treatment after discharge, purification and storage of biogas. The output and quality of biogas are mainly improved by improving pre-treatment technology and adding some substances. Pre-treatment can change the physical, chemical and biological characteristics of digested sludge, so as to improve its degradability, reduce sludge residence time and improve biogas production. Widely used pre-treatment includes thermal, chemical, ultrasonic and ozone oxidation. (Akcakaya, M., Tuncay, S. & Icgen, B. 2022)

In the single-stage anaerobic digestion (SAD) process, the hydrolysis, acidification, acetylation and methane generation of sludge take place in the same reactor during anaerobic fermentation, which requires low cost. From the perspective of microorganisms, hydrolysis and acidification are completed by facultative anaerobes, and the production of acetyl and methane is completed by obligate anaerobes. The time and optimal pH of various bacteria in each step are different. In the production of acetyl and methane, obligate anaerobic bacteria are vulnerable to the volatile fatty acids (VFAs) produced in the previous steps. It is difficult to maintain the balance of microorganisms. Therefore, two different reactors are usually used, hydrolysis acidogenic reactor and acetyl and methane producing reactor, two-phase anaerobic digestion (TAD). In the research of Akcakaya, Tuncay, & Icgen (2022), TAD reactor is used, as shown in Figure 8. (Akcakaya, M., Tuncay, S. & Icgen, B. 2022.)

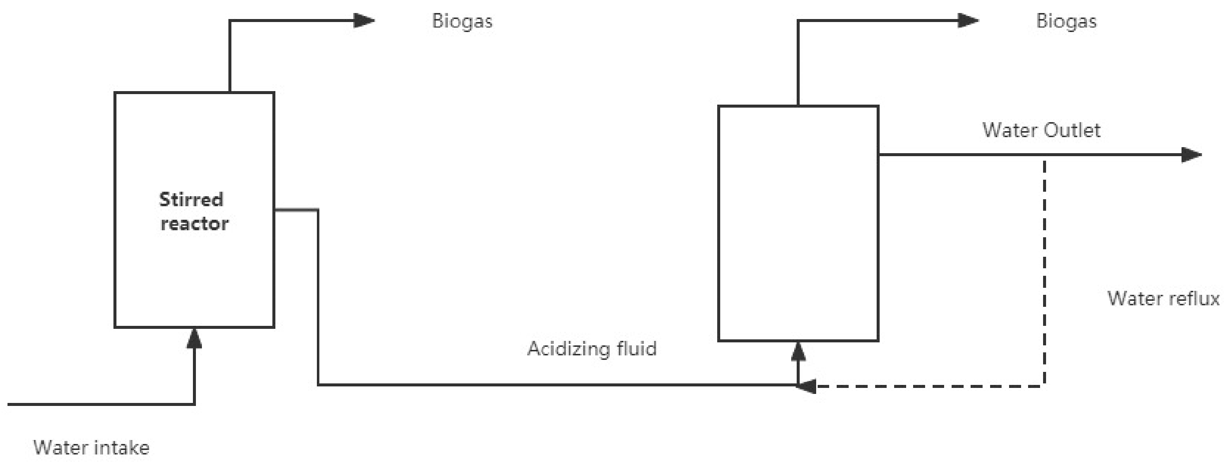


FIGURE 8. TAD series reaction system (adapted from Akcakaya, M., Tuncay, S. & Icgen, B. 2022.)

TAD process consists of two series reactors. In the TAD system, the treated municipal sludge is fed from the acid producing reactor. The hydrolysis and acidification of sludge are carried out in acid producing reactor. Hydrogen rich biogas is produced in the acid producing reactor and VFAs is released in the liquid solution. The acidogenic reactor and the methanogenic reactor are connected through a pump. The VFAs released in the acidogenic reactor and the residual biodegradable substances will be transported to the methanogenic reactor through the pump and converted into methane and carbon dioxide. The TAD process enables the growth of acidogenic bacteria and methanogens under optimum environmental conditions. This is not only maximizing the activity of each microorganism, but also improving the treatment effect, so as to improve the volume load rate, reduce the reactor volume and increase the operation stability. (Akcakaya, M., Tuncay, S. & Icgen, B. 2022)

4.2 Principle of sludge fermentation

Sludge fermentation is usually divided into three stages: hydrolysis stage, acidogenic stage and methanogenic stage. Most of the complex organics in sludge cannot be dissolved in water. They must be hydrolyzed by extracellular enzymes secreted by fermentation bacteria before they can be absorbed and utilized by microorganisms. Fermentative bacteria absorb soluble substances into cells and convert them into organic acids, alcohols and a certain amount of hydrogen and carbon dioxide through fermentation. Figure 9 is a phased summary of sludge fermentation. The total amount of acetic acid, propionic acid and butyric acid in the fermentation broth is called total volatile acid (TVA). (Choudhury, S., Saha, B., Haq, I. & Kalamdhad, A. 2022, 277-297)

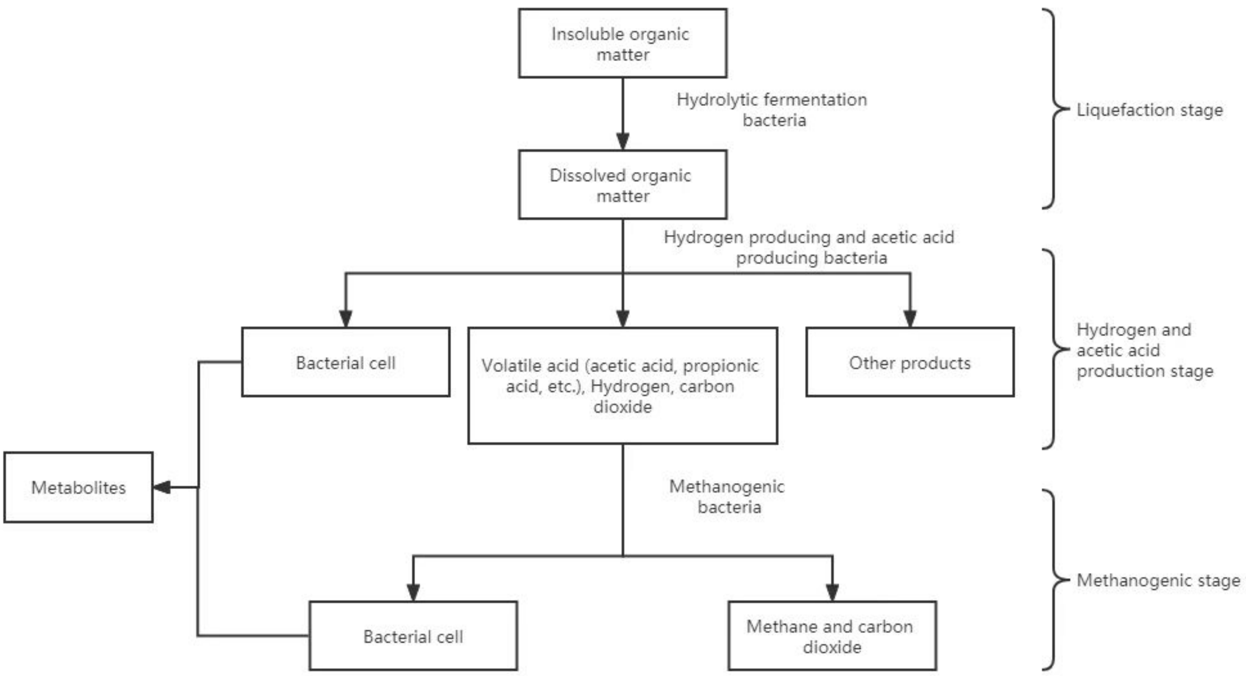


FIGURE 9. Three stages of sludge fermentation principle (adapted from Hassan, K., Abdel-Karim, A., Al-Shemy, T., Rojas, P., Sanz, L., Ismail, H., Mohamed, G., El-gohary, A. & Aly A. 2022, 1059-1071)

In the acid production stage, except formic acid, acetic acid and methanol, other organic acids and alcohols cannot be used by methanogens, which must decompose them into acetic acid, hydrogen and carbon dioxide. Hydrogen consuming acetic acid producing bacteria, also known as high acetic acid bacteria, are a kind of mixed trophic bacteria that can both autotrophic and heterotrophic life. They can not only use hydrogen and carbon dioxide to produce acetic acid, but also metabolize acetic acid. Through the activities of the above microorganisms, various complex organics can produce organic acids, hydrogen and carbon dioxide. (Choudhury, S., Saha, B., Haq, I. & Kalamdhad, A. 2022, 277-297)

5 CONCLUSION

With the scientific and technological progress of human society, the solutions to energy and environmental problems will become the most important and fundamental. The excessive use of fossil fuels has led to the depletion of energy. Finding new energy has become the main goal of people. Biomass energy is the energy stored in biomass by solar energy in the form of chemical energy, so biomass is regarded as an important energy, in which sewage sludge has more significant advantages.

Traditional sludge disposal methods have many problems, and the sludge has not been fully utilized. In order to avoid the pollution of ecological environment, save disposal costs and maximize the benefits of resources, it has become the goal to turn sludge into energy. The methods of landfill, sea dumping and incineration of sludge are very direct but they will cause pollution and waste resources.

The sustainable utilization of sludge has undoubtedly become a win-win solution. On the one hand, it solves the problem of environmental pollution caused by sludge, and hydrogen and biogas are renewable energy. On the other hand, it relieves the pressure on energy supply. However, the availability of hydrogen remains low, and the production efficiency of biogas needs to be optimized. Due to the immature technology, small scale and high cost, these new energy sources have not been fully utilized like fossil energy.

To sum up, the advantages outweigh the disadvantages. Anaerobic fermentation, plasma gasification and supercritical water gasification have proved to be successful technologies. With the maturity of technology and the expansion of production scale, these production processes can be realized on a large scale and the output can be increased.

REFERENCE

Akcakaya, M., Tuncay, S. & Icgen, B. 2022. *Two-stage anaerobic digestion of ozonated sewage sludge predominantly took over by acetotrophic methanogens with increased biogas and methane production*. 317(0016-2361). Available at: https://doi.org/10.1016/j.fuel.2022.123434. Accessed 12 January 2022.

Bhat, S., Cui, G., Li, W., Wei, Y., Li, F., Kumar, S. & Ameen, F. 2021. Chapter 11 - Challenges and opportunities associated with wastewater treatment systems. *Current Developments in Biotechnology and Bioengineering*, 259-283.

Choudhury, S., Saha, B., Haq, I. & Kalamdhad, A. 2022. 17 - Use of petroleum refinery sludge for the production of biogas as an alternative energy source: a review. *Advanced Organic Waste Management*, 277-297.

Ciuffi, B. 2020. Supercritical Water Gasification. Available at: https://encyclopedia.pub/2737. Accessed 21 January 2022.

Casademont, P., García-Jarana, M., Sánchez-Oneto, J., Portela, J. & Ossa, E. 2017. Supercritical water gasification: a patents review. *Rev Chem Eng*, 33, 237-261.

Dong, S. 2020. *Food waste as a raw material for biofuel production*. Centria University.

Fan, Q. 2018. *Methane potential of municipal sludge in anaerobic codigestion process boosted with glycerol*.

GlobalSpec's Engineering360. 1999. Dewatering Equipment Information. Available at: https://www.globalspec.com/learnmore/manufacturing_process_equipment/filtration_separation_products/dewatering_equipment

GN Solids Control. 2007. Sludge dewatering decanter sold to sewage treatment plants in Southeast Asia Market Available at: http://oilfield.gnsolidscontrol.com/sludge-dewatering-decanter-sold-to-sewage-treatment-plants-in-southeast-asia-market/. Accessed 19 January 2022.

Hydromo 2021. *Dissolved Air Flotation (DAF) Systems*. Available at: https://industrytoday.com/dissolved-air-flotation-daf-systems/. Accessed 7 January 2022.

Hassan, K., Abdel-Karim, A., Al-Shemy, T., Rojas, P., Sanz, L., Ismail, H., Mohamed, G., El-gohary, A. & Aly A. 2022. Harnessing Cu@Fe3O4 core shell nanostructure for biogas production from sewage sludge: Experimental study and microbial community shift. *Renewable Energy*, 188(0960-1481), 1059-1071.

Hwang, I., Kang, H., Lee, I. & Oh, J. 2012. Assessment of characteristic distribution of PCDD/Fs and BFRs in sludge generated at municipal and industrial wastewater treatment plants. *Chemosphere*, 88(7), 888-894.

Ibrahim, A.& Akilli, A. 2019. Supercritical water gasification of wastewater sludge for hydrogen production. *International Journal of Hydrogen Energy*, 44(21), 10328-10349.

Shandong Better Environmental Protection Technology Co. 2006. Belt Filter Press, Filtration equipment. Available at: http://wastewater-plant.com/2-3-belt-filter-press.html. Accessed 15 January 2022.

Jebrail, A. 2016. *Wastewater Treatment Process*.

Kätkä, K. 2013. *Laboratory testing methods for centrifugal sludge dewatering processes*.

Lee, S., Tsang, Y., Lin, K. & Lee, J. 2022. Employment of biogas as pyrolysis medium and chemical feedstock. *Journal of CO_2 Utilization*, 57.

Lei, P. 2009. *Sludge Treatment and Disposal.*

Nyyssönen, V. 2015. *Sewage sludge treatment for energy purpose in China.*

Qi, H., Cui, p., Liu, Z., Xu, Z., Yao, D., Wang, Y., Zhu, Z. & Yang, S. 2021. Conceptual design and comprehensive analysis for novel municipal sludge gasification-based hydrogen production via plasma. *Energy Conversion and Management*, 245.

Rivera, I., Schröder, U. & Patil, S. 2019. Chapter 5.8 - Microbial Electrolysis for Biohydrogen Production: Technical Aspects and Scale-Up Experiences. *Microbial Electrochemical Technology*, 871-898.

Schmieder, H., Abeln, J., Boukis, N., Dinjus, E., Kruse, A., Kluth, M., Petrich, G., Sadri, E. & Schacht, M. 2000. Hydrothermal gasification of biomass and organic wastes. *The Journal of Supercritical Fluids*, 17(2), 145-153.

Shankar, R., Kumar, S., Prasad, K. A., Khare, P., Varma, A. & Yadav, V. 2021. Chapter 9 - Biological wastewater treatment plants (WWTPs) for industrial wastewater. *Microbial Ecology of Wastewater Treatment Plants*, 193-216.

Sillero, L., Solera, R. & Perez, M. 2022. Anaerobic co-digestion of sewage sludge, wine vinasse and poultry manure for bio-hydrogen production. *International Journal of Hydrogen Energy*, 47(6), 3667-3678.

Sautya, M. 2018. Sludge Drying Bed – Wastewater Treatment. Available at: https://civil-noteppt.com/sludge-drying-bed/. Accessed 19 January 2022.

The Main Advantages of Sludge Drying Beds. Available at: https://www.climate-policy-watcher.org/wastewater-sludge/drying-beds.html. Accessed 20 January 2022.

Tilley, e., ulrich, l., luethi, c., reymond, p. & zurbruegg, c. Activated Sludge. *Compendium of Sanitation Systems and Technologies.* Available at: https://sswm.info/factsheet/activated-sludge. Accessed 22 January 2022.

Veras, T., Mozer, T. & César, A. 2017. Hydrogen: Trends, production and characterization of the main process worldwide. *International Journal of Hydrogen Energy*, 42(4), 2018-2033.

Wang, K. & Nakakubo, T. 2021. Strategy for introducing sewage sludge energy utilization systems at sewage treatment plants in large cities in Japan: A comparative assessment. *Journal of Cleaner Production*, 316.

Wang, M., Mao, M., Zhang, M., Wen, G., Yang, Q., Su, B. & Ren, Q. 2019. Highly efficient treatment of textile dyeing sludge by CO2 thermal plasma gasification. *Waste Management*, 90, 29-36.

What is Dissolved Air Flotation(DAF). Available at: https://www.shanleypump.com/edur-what-is-dissolved-air-flotation-daf.html. Accessed 20 January 2022.

Zahedi, S., Sales, D., Romero, L. & Solera, R. 2013. Hydrogen production from the organic fraction of municipal solid waste in anaerobic thermophilic acidogenesis: Influence of organic loading rate and microbial content of the solid waste. *Bioresource Technology*, 129, 85-91.