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Developing a Novel Approach for Sludge Treatment Using Microwaves Technology

David Yu, Wendy Li

Tsinghua International School, Beijing, China
Email: davidyu02@outlook.com, wendylithis@yahoo.com

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Abstract

The purpose of this research is to find a method that can improve the cost and efficiency of sludge treatment. Currently, large amounts of sludge are produced every day, but sludge treatment is neither efficient nor profitable. To improve the sludge treatment process, we proposed the method of using microwave technology to treat sludge. We hypothesized that using microwave technology, we can reduce the volume of the sludge up to 90%, and can save more energy and time comparing to the traditional methods that we are currently using to treat the sludge. To prove our hypothesis, we designed an experiment to compare the solid-liquid boundary height and the solid-liquid mass ratio of the sludge treated by the conventional method and the microwave technology. Prime temperature and time found for dewatering sludge are 70 Celsius degrees and five minutes. The results were rather surprising, as microwave heating demonstrated no significant advantage over conventional heating. The solid-liquid boundary height of sludge heated by conventional and by microwave methods are 22.34 mL and 22.56 mL; the solid-liquid mass ratio of sludge using conventional heating and microwave heating at 70 Celsius degrees are 14.28% and 14.55% (by separation with filter press), or 9.82% and 9.89% (by centrifugation). In conclusion, the difference is negligible.

Keywords

Municipal Sewer Sludge, Sludge Dewatering, Microwave Treatment, Intracellular Water, Thermal Conditioning, Solid Liquid Separation

1. Introduction

Wastewater sludge is created during the process of sewage water treatment; the sludge usually accounts for about 0.3% of the water volume. The toxic sludge poses as a problem of displacement, and current methods are by simply displacing it at landfills or dewatering it (OECD, 2020). The sludge, after proliferation in the final sedimentation tank, has a water content of about 98%. Existing methods, however, are not able to significantly drop this value (filter press can usually drop the water content to about 75%, and sometimes down to 65% using extreme pressure), as the majority of the water are intracellular water, meaning that they are trapped inside the microorganisms living inside the sludge. Conventional methods of sludge heating are not favored either as it is financially unreasonable. This experiment hypothesizes that heating sludge using microwaves can be an effective alternative able to significantly lower the water content of the sludge.

Microwaves are waves with wavelengths ranging from 1 mm to 1 m and frequencies between 300 MHz and 300 GHz. Heating by microwave is from the interaction between the molecules' dipoles and the changing electromagnetic fields of the microwave (Grübel, 2011). The emitted wave has a high frequency resulting it rapidly changing its electric field direction. Polar molecules, such as water, tend to align their dipole moments toward the electric field. Since the field is constantly changing, the water molecule is also changing its direction. This rapid molecular rotation and migration cause friction and collision between water molecules, eventually resulting in heat. Since heat is carried by the electromagnetic waves, the irradiation of microwave generators allows sludge to be heated dynamically, with the heat focused at the center of the space. The heating then breaks the cell structure of microorganisms, release the water trapped inside, and dramatically reduce the volume of sludge (Grübel, 2011).

Microwaving is much more efficient compared to traditional methods of heating, since the energy is transferred via waves instead of contacting matter. In other words, microwaving radiation penetrates through the nonpolar organic molecules and directly heat the water molecules inside and around the cell membranes. The heating and intense vibration of water molecules eventually break the cell structures. As the water is no longer inside the cells, it can be easily extracted via traditional methods such as centrifuge or condensation. Since water usually accounts for over 95% of the volume of sludge, the liberation of water enclosed in cellular structures can lead to a reduce volume of sludge by over 90% (OECD, 2020). The resulting sludge, as biofuel, has great energetic value.

The treatment of sewage sludge is categorized in the funding of public service of sewage treatment, as the contemporary processing of sewage sludge, although complete, is not profitable. Sewage sludge—the by-product of wastewater treatment—is still a burden of municipal funding on sewage water treatment.

Right now, huge amounts of sludge are produced each day. Sewage sludge is the waste by-product produced by wastewater treatment plants, and its volume is usually 3/1000 of its raw wastewater input. Correspondingly, the production of sludge in China in 2015 was 35 million tons, and the number is continuously increasing (Yang et al., 2015). Europe produces around 20 million tons of wet sludge, and the US produces around 10 million tons of dry sludge annually (Venkatesan, 2015). Yet, efficient sludge treatment technology is still in need for more cost-effective and efficient treatment of increasingly large amounts of sludge.

Those sewage sludge produced are often toxic, radioactive and hard to handle, and are thus left unprocessed and disposed of in big cities. Currently, the metal-rich sludges produce potential risks to our society, including damage to human organs under accidental exposure, water pollution, etc. There are two main negative features of sludge. The first one is poor settling, which means sludge is hard to settle and control. The second problematic characteristics of sludge are its poor compactness. There are always water and gas trapped in the sludge that makes it hard to be collected into a compact matter, therefore making it hard to be stored or processed.

Currently in China, more than 80% of sludge is disposed by improper dumping (Researchgate, 2015). Regarding proper disposal, the sanitary landfill is the commonest, followed by land application, incineration and building materials. However, these treatments are facing increasing pressure due to lack of land space for landfills and the stricter regulations regarding pollution of the farmlands and water bodies.

There were also some technologies developed for the purpose of sewage sludge reduction, such as ozone, ultra-sonic, mechanical and heating. But the existing technologies either cost too much (i.e., the ozone and heating technology which consumes massive amount of power), cannot sufficiently reduce the amount of sewage (i.e., the mechanical technology that uses machine to squeeze the sludge and can only reduce the amount of water contained by 5%), or are harmful to the device itself (i.e., the ultrasonic technology which harms its device) (Uluko, 2014).

Common methods of dewatering include filtration, centrifugation, and sometimes evaporation. Evaporation is a cheap method usually used in developing countries where funds for sanitation are limited. Evaporation is usually performed by disposing the collected sludge on great "drying beds" where they evaporate and collect their water content under the sun, and the remnant solids are then collected to be dealt with as waste or sold as agricultural fertilizers. Drying beds usually have four layers composed of sand and gravel serving as a filter between the dried sludge and evaporate water that are then collected by pipes underneath. Such method, despite their cheap cost, is obviously ineffective to meet the rapid production of the sludge of large metropolises due to its inefficiency in time and space.

Meanwhile, filtration and centrifugation meet the need for efficiency in the treatment of sludge. Yet, such methods still cannot release the majority of the water enclosed inside the cells of the microorganisms and eventually yield a 20 to 45 percent reduction of water—fairly low compared to the 92 percent achieved by microwave treatment. Nonetheless, because of the high percentage of dry biomass, the biosolids produced by microwave treatment can be used as biofuel (Compost-Turner, 2007). Biosolids of sewage sludge and fecal sludge produced under experimental conditions yielded caloric values of 23 MJ/Kg and 16 MJ/Kg, respectively, while that of coal is merely 7.9 MJ/Kg (Mawioo et al., 2017). On the other hand, the biosolids from conventional dewatering treatments, due to their high percentage of water, can only be sold as fertilizers, since their caloric value is too low. Overall, microwave treatment for sludge is more efficient than dewatering methods such that its end-product biosolid is denser, meaning a lower fee of transportation and greater value as fuel.

Incineration of sludge is less common due to emission concerns and its need of auxiliary fuel for combustion. Better versions of incineration treatment plants impose a method of waste-to-energy reduces its need for outside sources of energy. It is reported, however, that the obtained sludge after incineration does not have sufficient energy yield to supplement the power required to dry sludge water via either evaporation or centrifugation (ISWA's Working Group on Sewage & Waterworks Sludge, 1997). The advantage of incineration treatments is that they are insensitive to the composition of sludge used and the solid end-product sludge have high caloric value. Microwave heating, which is also based on heating, meet these criteria as well. The part where microwaves are better is eco-friendliness. The burning of sludge, even for the waste-to-energy method, still poses dangerous climatic concerns; on the other hand, MW generators operate on electricity while the temperature is contained under 140 degrees Celsius to prevent combustion of organic matter.

Another method of treating sludge is composting, which is based on aerobic degradation of the organic sludge through forced aeration and mechanical turning of compost (Chow et al., 2020). It aims to gain agricultural benefits from the nutrient and organic values within the sludge. In composting, various features of the sludge; which include the moisture, the creation level and the nutrient level; need to be considered in order to ensure that the sludge has sufficient organic matter as well as relevant water content to be composed (Chow et al., 2020). Therefore, the condition for a sludge to be successfully composed is strictly limited. For example, according to European Environmental Agency's general reference, the water content of a compostable sludge should be higher than 55% while lower than 60%, since water content too low could limit the rate of composting and water content too high could reduce the temperature, porosity and thus the oxygen concentration (ISWA's Working Group on Sewage & Waterworks Sludge, 1997). Similar limitations are also set on the pH level, carbon to nitrogen ratio and the bacterial activity of the sludge. As a result, the process of composting sludge not only requires a huge amount of time and energy but also costs more than any other treatment. Even so, the sludge that went through the composing process has a high possibility of not meeting the condition and thus has a low value.

In a nutshell, the water percentage in sludge can only be reduced from 96% to 70% because the majority of the liquids that are enclosed inside the prokaryotic cells, protected by its cell walls and membranes (Xu et al., 2019). Conventional physical methods; such as centrifugation, filtering and plate compression; cannot pass the 70% threshold as they fail to breach the cell walls, leaving the majority of the water intact inside the still yet complete organisms.

2. Experimental Procedures

The experiment divides into two major parts: preparation and treatment. The preparation is to find the prime values for the controlled variables of the experiment, such as that of the temperature, compression time and pressure, amount of clarifying agent added, etc.

A) Sludge volume-reduction methods:

1) Centrifugation

2) Filter press

3) Thermal hydrolysis

B) Experimenting with the feasibility of microwave sludge volume-reduction

1) Experiment I: Finding the optimal temperature and heating time

a) Equipment: Type HKX-H1C1B microwave chemical furnace, beaker, graduated cylinder, test tubes

b) Experiment procedure:

i) Add 300 ml of activated sludge each into five test tubes, use the microwave chemical furnace to heat them to 30, 40, 50, 60, 70, degrees Celsius, respectively. Maintain the temperature for five minutes and observe the height of the solid-liquid boundary.

ii) Add 300 ml of activated sludge each into five test tubes, use the microwave chemical furnace to heat them to 70 degrees Celsius, and maintain the temperature for 1 min, 3 min, 5 min, 7 min, 9 min, respectively. Then observe the solid-liquid boundary.

c) Expected result:

i) Under the same time, as the temperature rises, the solid-liquid boundary first slowly drops and reaches its valley at seventy degrees. As the temperature continues to rise, the boundary level begins to rise slowly. Thus, 70 Celsius degrees is the optimal temperature for microwave thermal sludge treatment.

ii) Under the same temperature, as the maintenance time elongates, the solid-liquid boundary drops slowly and reaches its valley at five minutes. As the duration time continues to increase, the boundary height bounces back up. Thus, five minutes is the optimal time length for the sludge's heating.

2) Experiment II: Finding the solid-liquid boundary of the natural sedimentation

a) Experiment equipment: beaker, graduated cylinder

b) Experimental steps:

i) Obtain 300 ml unprocessed activated sludge and put it into the graduated cylinder

ii) Add flocculants according to the 3‰ concentration ratio into the cylinder, leave the sludge to sediment for thirty minutes

iii) After the flocculates react thoroughly with the sludge and the solid-liquid partition occurs, observe the solid-liquid boundary height in the graduated cylinder.

c) Expected result: the sludge after microwave treatment has the lowest solid-liquid boundary, indicating the best dewatering effect.

3) Experiment III: finding solid-liquid ratio through centrifugation

a) Equipment: tubular centrifuge, beaker, graduated cylinder, test tubes

b) Procedure:

i) Obtain 300 ml each of unprocessed activated sludge, microwave heated sludge, and conventionally heated sludge

ii) Put them into the tubular centrifuge and centrifuge them at 3000 revolutions per minute.

iii) Calculate the mass ratio of the solid particles and liquid.

c) Expected result: the sludge after microwave treatment has the lowest solid-liquid boundary, indicating the best dewatering effect.

4) Experiment IV: finding solid-liquid ratio through filter press

a) Equipment: Type CRBr (200 mm × 200 mm) multi-layered filter press, graduated cylinder, beaker

b) Procedure:

i) Obtain 300 ml each of unprocessed activated sludge, microwave heated sludge, and conventionally heated sludge

ii) Add them into the press filter and filter them

iii) Calculate each of their solid-liquid mass ratio

c) Expected result: the sludge after microwave treatment has the lowest solid-liquid boundary, indicating the best dewatering effect.

3. Results Analysis and Discussions

The experiment was carried out in said procedure. Results are as followed:

Experiment I: (Table 1 and Table 2).

Experiment II: (Table 3).

Experiment III: (Table 4).

Experiment IV: (Table 5).

4. Discussion

There has been much discussion in recent years about the application of microwave heating in sludge treatment. However, as this experiment has proven, low temperature microwave heating does not have an outstanding dewatering effect compared to the conventional methods. Attempts can still be made by adding other chemical components that can help flocculate the sludge. Currently, best ways to break the cellular structure and free the intracellular water are still heating sludge to 150 degrees under high pressure.

5. Conclusions

The results of Table 1 and Table 2 show that temperature and heating time have a significant positive impact on the dewatering of sludge, and municipal sludge at room temperature has poor dewatering capability, as the solid-liquid boundary height decreases as time (before reaching the five minute threshold) and temperature of the heating increases. In Table 3, the solid-liquid boundary height of unprocessed sludge is 23.78 mL while that height of heated sludge is 22.34 mL (conventional heating) and 22.56 mL (microwave heating). The differences are less than 2 mL, which is very small considering the amount of work applied to the sludge. In Table 4 and Table 5, the solid-liquid mass ratio of sludge after heating at 70 degrees is only about two to four percentiles higher than that of sludge under room temperature. The experiment shows that, at 70 degrees Celsius, microwave irradiation has a negligible impact on the sludge's dewatering capability, which is contradictory to the previous hypothesis.

According to *Research on the Municipal Sewage Sludge Treatment Technology Based on Hydrothermal Conditioning* by Doctor Qiao Wei from Tsinghua

Table 1. Chart of solid-liquid boundary height in respect of time, showing that the longer time the sludge is heated, the lower its solid-liquid boundary height.

Heating time	1 min	3 min	5 min	7 min	9 min
Solid-liquid boundary height (mL)	27.88	25.27	22.56	22.57	22.56

Table 2. Chart of solid-liquid boundary height in respect of temperature, showing that the higher the temperature the sludge is heated under, the lower its solid-liquid boundary height.

Heating temperature	30˚C	40˚C	50˚C	60˚C	70˚C
Solid-liquid boundary height (mL)	28.23	26.37	25.12	23.48	22.56

Table 3. Chart of solid-liquid boundary height in respect of heating method, showing that the difference of the solid-liquid boundary height of sludge heated by microwave and sludge heated by conventional method is negligible.

	Room temperature unprocessed sludge	Conventionally heated sludge (70˚C)	Microwave heated sludge (70˚C)
Solid-liquid boundary height (mL)	23.78	22.34	22.56

Table 4. Chart of solid-liquid mass ratio in respect of heating method found through centrifugation, showing that the difference of the solid-liquid mass ratio of sludge heated by microwave and sludge heated by conventional method is negligible.

	Room temperature unprocessed sludge	Conventionally heated sludge (70˚C)	Microwave heated sludge (70˚C)
Solid-liquid mass ratio	7.33%	9.82%	9.89%

Table 5. Chart of solid-liquid mass ratio in respect of heating method found through filter press, showing that the difference of the solid-liquid mass ratio of sludge heated by microwave and sludge heated by conventional method is negligible.

	Room temperature unprocessed sludge	Conventionally heated sludge (70˚C)	Microwave heated sludge (70˚C)
Solid-liquid mass ratio	10.29%	14.28%	14.55%

University, the heating of microwaves under 100 degrees Celsius have minimal effects on the composition of sludge, but exceeding 100 degrees have a significant impact on the sludge (Qiao, 2008). This theory matches with this article's results.

In this experiment, the heating temperature did not exceed 70 degrees Celsius because the apparatus cannot withstand higher temperatures. As known, the microwave cannot have direct contact with metal, meaning the container's material can be only porcelain, glass, or plastic. Such material that can withstand high temperatures requires special processing, which is out of the experiment's budget and particularly unattainable during this time of pandemic when the experiment is carried out.

The irradiation of microwaves changes the organic structures within the sludge—specifically by destroying the cell walls and releasing the intracellular water—and enhances the dewatering effect of sludge treatment using a filter press. The initial hypothesis assumed that the molecular structures of the microorganisms could be dismantled and liberate the bulk water in activated sludge floc with a moderately high microwave heating temperature (50 - 70 degrees). The opposite result can be due to an unanticipated deformation of the cellular proteins that strengthen the cell walls from breaking or an undervalued Van der Waals' intermolecular force of the cell. Thus, while heating at the above boiling temperature of water under normal pressure does have a significant impact on the sludge composition, the treatment of microwave heating at lower temperatures results to be insufficient (Qiao, 2008).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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