

INTENSIFICATION AND MONITORING OF ANAEROBIC FERMENTATION OF SEWAGE SLUDGE FROM THE MEAT INDUSTRY

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ABSTRACT

Anaerobic digestion is a complex process, and the right quality of feedstock is essential for its proper completion. Although, meat industry wastewater is not ideal feedstock for biogas production, its properties can be improved by pre-treatments. In our chosen pre-treatments, we added magnetite nanoparticles to the sludge and then irradiated it with microwaves at different power levels. Monitoring the fermentation is crucial, especially in industrial practice. We monitored the progress by measuring the dielectric properties of the sludge samples. Our results show that dielectric measurements are a promising alternative for monitoring the anaerobic fermentation because there is a clear correlation between the changes in the value of the dielectric constant and the progression of the fermentation. Our results also clearly support the positive effect of the chosen pretreatments on the amount of biogas produced during fermentation. While the amount of gas increased, the methane content of the biogas produced did not change as verified by gas analysis.

Keywords: sewage sludge, anaerobic fermentation, biogas, dielectric parameters, microwave irradiation

1. INTRODUCTION

Over the past century, due to the rapid growth of industrial production and the world's population humanity is facing two major problems: waste accumulation and the depletion of non-renewable energy sources. Similar to other types of wastes, the amount of wastewater generated by human activity has increased significantly. The waste produced in the largest quantities during wastewater treatment processes is sewage sludge. Sewage sludge is the residual viscous liquid produced during the dewatering of wastewater.

In Europe, an average of 90g of sewage sludge per capita (in dry matter) is generated daily. Considering that the dry solids content of sewage sludge typically ranges between 0.25% and 12%, even the most optimistic estimates suggest that Europe's wastewater treatment infrastructure processes a substantial amount of sewage sludge every day [1].

This extreme amount of sludge makes it important develop as efficient sewage sludge processing and recovery methods as possible. One promising approach involves utilizing sewage sludge as feedstock for anaerobic fermentation to produce biogas, a renewable energy source. The huge advantage of this method is that not only is the biogas produced as a final product is a suitable energy source, but the process often kills pathogenic microbes that were present in the original wastewater and stabilizes the sludge [2]. So the material left over after fermentation can be usually safely used for soil improvement.

However, not all wastewater is equally suitable as feedstock for biogas production. The meat industry requires large quantities of clean water and, depending on the specific plant, the technology used and the efficiency of the water management in the plant, a large proportion of the water used is heavily contaminated. The most common and most abundant contaminants are blood, fat, bone fragments, meat scraps, hair, feathers, feces, as well as salt from marinades and chemicals used for disinfection and cleaning to meet strict hygiene requirements [3].

Therefore, the meat industry could provide a significant amount of sewage sludge as feedstock for biogas production, but this sludge in itself is more than often not optimal. In the biogas production process, microbial bacteria and specific archaea degrade the organic matter in the feedstock under anaerobic conditions, producing an energy-rich gas mixture which has many applications. The quality of the feedstock is essential

to ensure the optimal fermentation process and the quality of the produced biogas [4]. Most of the nutrients important for microbial growth are found in flocks and consequently, has relatively low bioavailability. Furthermore, residual disinfectants and detergents can inhibit the proper activity of the gas-producing microbes. Due to these properties, it is advisable to pre-treat meat industry sludge before using them as feedstock for biogas production to improve their properties and to be able to extract biogas with higher yields and better quality [5].

The aim of this study is to investigate the effects of microwave pre-treatment on meat industry sewage sludge in the presence of magnetite nanoparticles on the amount and CH₄ content of the produced biogas. Additionally, we also analyzed the applicability of dielectric measurement to monitor the fermentation process.

2. MATERIALS AND METHODS

The sewage sludge used in our experiments originated from the Pick Szeged Zrt. meat processing company's plant.

For the microwave pre-treatments we used the Labotron500 microwave device. The device is capable of generating a multimode electromagnetic field, meaning during operation, several electromagnetic wave patterns are generated in the resonator of the device. It has a magnetron core and can generate electromagnetic waves at 2.45 GHz. The pretreatments were carried out at two different power levels: 250 W and 500 W. To keep the irradiation dose constant regardless of the power level, we adjusted the irradiation time accordingly: the microwave treatment was applied for 1.5 minutes at 500 W and for 3 minutes at 250 W.

One of the problems with microwave sludge treatment is the fact that the heating is inhomogeneous. Therefore, to help uniform heating, I added 15 cm³ of magnetite nanoparticle suspension to the wastewater sludge before the microwave pre-treatment. The suspension had a concentration of 0.71 g/100 ml, with an average particle size of 110 nm. Each sample contained 100 cm³ of wastewater sludge, to which I added 15 cm³ of magnetite nanoparticle suspension and 10 cm³ of inoculum sludge. The inoculum was added after the microwave treatment to ensure the necessary microbial count for the proper initiation and progression of the fermentation. The anaerobic fermentation took place in 250 cm³ laboratory glass fermenters sealed with PTFE septa. Biogas production was monitored by measuring the pressure increase inside the laboratory glass reactors using automatic WTW OxiTop IDS/B pressure sensor heads. After reading the pressure values, I collected biogas samples using a Hamilton syringe. The carbon dioxide and methane content of the gas samples was analyzed via gas chromatography at the Institute of Biology, Faculty of Science and Informatics, University of Szeged.

To monitor the dielectric parameters of the samples, I used an SPEAG DAK 3.5 open-ended dielectric measurement sensor (Schmid & Partner Engineering AG, Switzerland). The sensor was connected via a coaxial transmission line to a ZVL-3 vector network analyzer (Rohde & Schwarz, Germany), which enables measurements in the 200–2400 MHz frequency range. Dielectric properties were measured at the fermentation temperature of 38 °C.

3. RESULTS AND DISCUSSION

3.1. Examination of biogas production

We examined the effects of different pre-treatments on the quantity of produced biogas and the kinetics of biogas production. The amount of biogas generated in both the pre-treated samples and the control sample was determined by measuring the overpressure in the fermenters. The biogas volume was then calculated using a modified version of the ideal gas law based on the pressure measurements:

$$V_{biogas} = \frac{p_r \cdot V_r \cdot T_{norm}}{p_{atm} \cdot T_f} \quad (1)$$

The p_r [Pa] is the pressure measured in the fermenters, V_r is the gas volume [cm³], $T_n = 293$ K, which is the technical normal temperature, p_{atm} is the atmospheric pressure, i.e., 10^5 Pa, and $T_f = 311$ K, which is the fermentation temperature.

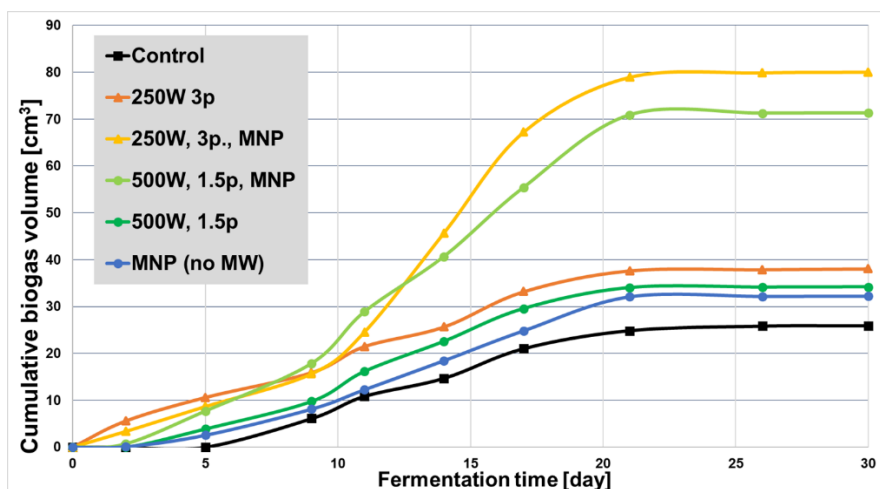


Figure 1. Changes in biogas production over fermentation time in control and pre-treated samples

The obtained results, plotted as a function of fermentation time, allow for easy comparison. This can be seen in Figure 1. The gas production results clearly show the stimulating effect of the selected pre-treatments on gas production, as the control sample produced less biogas than any of the samples pre-treated by us.

The most effective pre-treatment was the one conducted at 250 W for 3 minutes with the addition of magnetite particles: this method resulted in more than three times the gas production compared to the untreated sample. In both tested power levels, the presence of magnetite nanoparticles had a positive effect on the amount of biogas produced, as the highest yields were consistently observed in the samples that underwent the combined treatment compared to those that received only microwave irradiation. Based on the increase in biogas yield, it is likely that the two treatments—microwave pre-treatment and the application of magnetite nanoparticles—were not simply additive but also enhanced each other's effects. In the case of a strictly additive effect, the increase in biogas yield observed in the combined treatments would equal the sum of the yield increases from the individual pre-treatments. However, as seen in Figure 1, a greater increase was observed. This means that the amount of biogas produced increased more significantly than expected, indicating that the combination of the two treatments had a synergistic effect, making it more effective than applying them separately. One possible explanation for this is that magnetite nanoparticles act as hot spots during heating and successfully eliminate the temperature inhomogeneities caused by the selective heating profile of microwave energy transfer. More homogeneous heat treatment leads to more uniform and efficient sludge disintegration. Furthermore, my gas production results also show that the sample treated only with magnetite particles—used as a control for the microwave pre-treatment—also exhibited increased gas production compared to the untreated sample. This proves that the presence of metal nanoparticles stimulates gas production even without microwave heating, meaning their beneficial effect is not limited to the microwave pre-treatment process.

The results indicate that the mere presence of iron has a stimulating effect on microbial metabolism and activity. Although microbes cannot directly utilize elemental iron or iron oxides, they produce organic acids during fermentation that may contribute to the release of iron ions from iron oxides. These released iron ions

can then be absorbed and incorporated into microbial metabolism, making them biologically available and beneficial.

In the control sample, the onset of biogas production was observed the later compared to the other samples. This indicates that the pre-treatments not only had a beneficial effect on the total gas volume produced but also helped the initiation of gas production. In the treated samples, gas production began several days earlier than in the control. The likely reason for this earlier onset of gas production is the shortening of the lag phase. This means that the microorganisms in the fermentation culture adapted more quickly to the new conditions and reached the state necessary for cell division and intensive metabolic activity faster. On a large scale, such as in industrial applications, this effect could lead to significant cost savings.

3.2. Analysis of biogas quality

Of course, when biogas is used as an energy source, it's quantity is not the only important factor—it's quality must also be taken into account. For this reason, we wanted to examine how the selected pre-treatments influenced the composition of the produced gas. The useful component of biogas is methane, as its combustion allows biogas to be utilized as an energy carrier. From an energy perspective, the higher the methane content of a given biogas sample, the better it's quality. The gas composition was analyzed using gas chromatography. The CH₄-CO₂ ratio determined under different pre-treatment conditions averaged 83% in favor of methane, with a standard deviation of only 2.7%. This indicates that there was no significant difference in gas quality between the treated samples and the control. These results show that the applied pre-treatments increased the volume of the produced gas without negatively affecting its methane content. In other words, a larger quantity of biogas was generated while maintaining the same methane concentration. Thus, it can be concluded that the amount of CH₄ produced increased significantly as a result of the treatments.

3.3 Examination of monitoring the fermentation by dielectric measurements

Another focus of our research was to monitor the dielectric constant of sewage sludge samples throughout fermentation to determine whether it could be used as a reliable parameter for fermentation monitoring. We measured the dielectric constant values in the frequency range 200-2400 MHz.

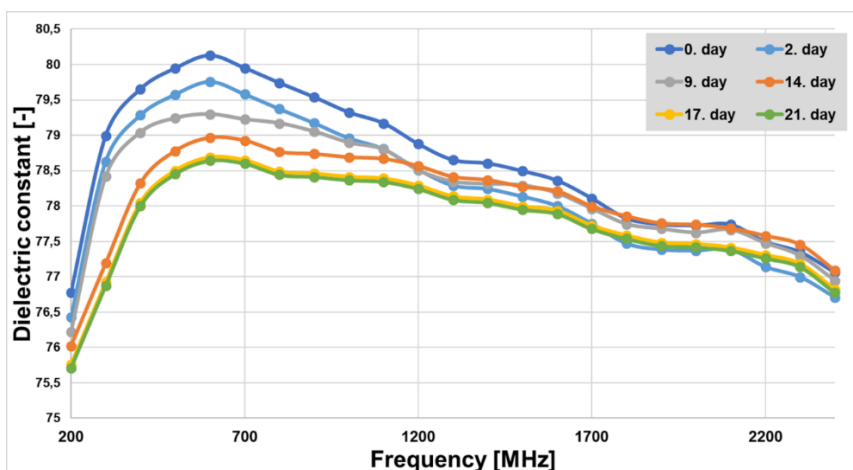


Figure 2. Changes in the dielectric constant of sewage sludge samples as a function of measurement frequency and fermentation progress

The dielectric properties of sewage sludge behave similarly to those of other water based systems. Throughout the entire fermentation process, the maximum value of the dielectric constant is consistently measured at the same frequency (around 600 MHz). However, the absolute maximum value gradually decreases as fermentation progresses. The decrease in the dielectric constant is more intense at lower frequencies because, beyond the relaxation frequency (where the dielectric constant reaches its absolute maximum within the examined range, in this case, around 600 MHz), the system can no longer follow the oscillating electromagnetic field. As a result, differences in dielectric properties gradually diminish, regardless of composition.

Based on this observation, as we approach the upper limit of the measured frequency range, this decrease becomes less noticeable. As shown in Figure 2, by the 17th to 21st day of fermentation, there is no significant frequency-dependent difference in the dielectric constant. This indicates that anaerobic degradation has reached a steady-state condition, where there is no significant biogas production. This suggests that the molecular changes that take place during the different stages of the anaerobic fermentation is also reflected in the change of the system's dielectric behavior. This means that the method based on the measurement of dielectric properties can be used to monitor the fermentation process.

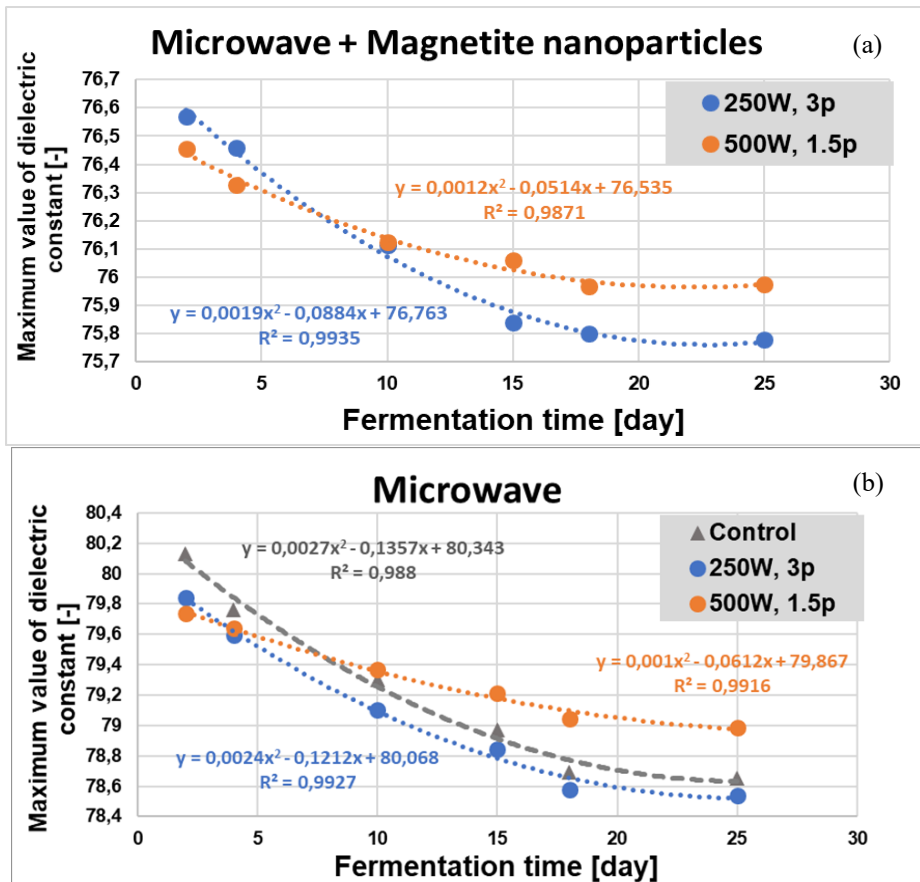


Figure 3. (a) Changes in the maximum dielectric constant of microwave pre-treated samples and the control sample during the fermentation process; (b) Changes in the maximum dielectric constant of samples subjected to microwave pre-treatment combined with magnetite nanoparticles during the fermentation process

Our results indicate that the characteristic decrease in the dielectric constant follows a similar trend regardless of the pre-treatment applied to the samples. In all cases, the decrease can be well described by a second-degree polynomial function, as supported by the consistently high R^2 values ($R^2 > 0.98$). Based on this, it can be concluded that the decrease in the dielectric constant shows a strong correlation with the progression of fermentation time, independent of the pre-treatment method. Since fermentation time inherently defines the different phases of anaerobic digestion, this correlation suggests that dielectric constant measurements could be used to monitor the process. This demonstrates that with proper calibration, determining the dielectric constant and its changes over time could serve as a method to track the anaerobic digestion of sewage sludge.

4. CONCLUSIONS

Our results show that microwave treatment with the addition of magnetite particles increases the amount of biogas produced during anaerobic fermentation without reducing its quality. The pre-treatment at 250 W combined with magnetite nanoparticles proved to be the best. The effectiveness of the 250 W treatment is not necessarily a result of the lower power, it is possible that the longer treatment time allowed the microwave treatment to have a more uniform beneficial effects. In the future, we plan to investigate the treatment time as an influencing parameter. The earlier start of gas production is probably due to the shorter lag phase. Thus, the bacteria of the fermentation culture adapt more quickly to the new conditions and reach the state necessary for division and intensive metabolic processes. On a larger scale, such as in industrial applications, this can lead to significant cost savings. If the microbes start their metabolic processes more quickly, the required temperature and mixing levels have to be maintained for a shorter period, reducing energy and operational costs.

It can also be seen from the results that the maximum value of the dielectric constant decreases steadily as the fermentation proceeds. This decrease is present regardless of the pre-treatment and follows a second order trend. This means that we can consider the measurement of dielectric properties. a non-destructive and real-time monitoring method for sewage sludge fermentation monitoring.

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