Cold-plasma application for enhancing methanogenesis in the anaerobic digestion of sewage sludge

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The volume of sewage sludge generated during wastewater treatment and the associated treatment costs have been steadily increasing, posing significant environmental and economic challenges. Sewage sludge is a by-product of wastewater treatment and consists of a complex mixture of organic and inorganic materials. Due to its high activity, when improperly disposed of, sewage sludge has the potential to contaminate soil and water resources, causing long-term damage to ecosystems (Oh Kyung et al., 2022).

As a result, there has been a growing focus on alternative technologies for the treatment and reduction of sewage sludge volume. Among these technologies, anaerobic digestion (AD) has emerged as a promising method to reduce sludge volume while generating renewable biogas (Gebreeyessus and Jenicek, 2016; Gross et al., 2021).

Anaerobic digestion consists of four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Wang et al., 2023). Among these stages, hydrolysis is often identified as the rate-limiting step in the treatment of sewage sludge (Preethi et al., 2022). The complex organic structure of sewage sludge makes it difficult to break down during the hydrolysis stage, resulting in low biogas production efficiency (Chen et al., 2008).

To overcome these limitations, various pretreatment methods have been developed to enhance the hydrolysis process and improve the overall efficiency of anaerobic digestion (Gahlot et al., 2022). One such promising method is cold plasma (CP), which has gained attention for its ability to break down complex organic molecules (Kim et al., 2024), and potentially improve methane production rates (Ortiz Vanegas and Kim, 2024). Despite its known ability to enhance hydrolysis, limited research has been conducted to explore the specific impact of CP on methane production rates and overall biogas yield during anaerobic digestion.

The primary objective of this study is to investigate the effect of cold plasma pretreatment on methane production in anaerobic digestion and to evaluate how residence time, in combination with CP pretreatment, influences biogas production efficiency. This study aims to investigate the impact of cold plasma (CP) pretreatment on methane yield and explore how CP can potentially optimize the hydrolysis phase in the anaerobic digestion.

In this study, sewage sludge (SS) was pretreated using cold plasma (CP) and subsequently subjected to anaerobic digestion in a continuous process for 35 days. Hydraulic retention time (HRT) was varied from 15 to 12, and then to 9 days to evaluate the influence of different HRTs on the methane production rate and volatile solids (VS) reduction. Application of the pretreated sewage sludge (PSS) was compared with that of untreated SS to assess the impact of CP on biogas production efficiency. Statistical techniques, including analysis of variance (ANOVA) and t-tests, were employed to evaluate the methane yield and the reduction in VS at each HRT. The electrical energy per order (EE/O) was also calculated to assess the energy efficiency of the CP pretreatment process.

Table 1. methane production in steady state (mL/day)

Division	SS-15	PSS-15	SS-12	PSS-12	SS-9	PSS-9
HRT (d)	15	15	12	12	9	9
CP treatment	O	X	O	X	O	X
CH_4 production (mL/d)	19.7	22.0	23.9	24.7	24.3	26.9
Ch_4 content (%)	46.3	50.4	47.6	49.7	46.5	49.7
Cumulative CH_4 (mL)	631.4	709.8	737.5	809.3	784.3	829.5

The results of this study indicated that cold plasma pretreatment significantly enhanced methane production during anaerobic digestion. As the HRT decreased, both the methane production rate and methane yield per unit of volatile solids increased. Specifically, the methane yield increased from 22% to as high as 79% per unit of volatile solids when CP pretreatment was applied across all HRTs.

These findings suggest that cold plasma pretreatment effectively improved the biodegradability of sewage sludge by reducing particle size and enhancing hydrolysis, which in turn accelerated the methanogenesis process. This study also demonstrated that CP pretreatment not only enhanced methane yield but also led to a significant reduction in volatile solids, contributing to more efficient sludge degradation.

Moreover, the analysis of the electrical energy per order (EE/O) revealed that cold plasma pretreatment is an energy-efficient process, providing a cost-effective and environmentally friendly alternative to conventional pretreatment methods. The cold plasma pretreatment process was found to require relatively low electrical energy (~419 kWh/m^3) compared to other pretreatment technologies (481~4,906 kWh/m^3). This makes CP pretreatment a promising solution for large-scale sewage sludge management, particularly in regions with limited land availability for disposal or incineration.

In conclusion, this study demonstrates that cold plasma pretreatment significantly improves methane production rates and overall biogas yield in anaerobic digestion by enhancing the hydrolysis phase of sewage sludge treatment. The application of CP pretreatment provides a valuable solution for overcoming the rate-limiting factors of hydrolysis, which are a major challenge in sewage sludge management. The increased methane production and reduced volatile solids indicate that CP pretreatment can effectively enhance the efficiency of the anaerobic digestion process, leading to a higher yield of renewable biogas and a reduction in the volume of sewage sludge. This research presents an eco-friendly, cost-effective, and energy-efficient alternative for sewage sludge treatment, providing significant potential for integrating cold plasma technology into large-scale wastewater treatment plants.

In summary, this study offers an innovative approach to improving the efficiency of both anaerobic digestion and sewage sludge management. It highlights the potential of cold plasma as an effective pretreatment method, with broad applications in sustainable waste management and renewable energy production.

Table 2. EE/O comparison by pretreatment method

Pretreatment method	Target component	EE/O (kWh/m^3)	Reference
Ultrasonication	TS	4,906	[1]
	VS	1,759	
H_2O_2-assisted Microwave	TS	554	[2]
	VS	481	
CP	TS	419	This study
	VS	434	

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