**Pulsed current in organic waste processing**

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**Abstract.** This study examines the challenges associated with cultivating methanogenic bacteria in isolated environments and the requirements for their effective integration into the main anaerobic digestion process aimed at intensifying methanogenesis. The article presents methods of applying pulsed electric current to accelerate methanogenesis during anaerobic conversion of organic waste in biogas systems commonly operated under the climatic conditions of Central Asia. The results indicate that electrical-discharge pretreatment of organic feedstock is among the key factors contributing to increased biogas yield in bioreactors. The optimal treatment parameters were identified as follows: discharge voltage U = 12 V, number of pulses n = 6, and capacitor capacitance C = 1.1 μF. It was also determined that relatively low-intensity pulsed current exhibits limited effectiveness in activating methanogens. Comparative analyses of biogas yields under various pulse regimes are provided.

**INTRODUCTION**

A wide range of methodologies aimed at enhancing the rate and stability of anaerobic digestion has been documented in the global literature [1–8]. Ensuring optimal conditions for anaerobic processes primarily requires strict control over the intrusion of free oxygen into the system throughout the digestion period, while also considering the specific characteristics of the methanogenic phase [9–14]. In numerous investigations, methanogenic bacteria have been cultivated in separate controlled media and subsequently introduced into the main digestion environment to accelerate methanogenesis. However, due to insufficient adaptation of these externally cultivated consortia, non-uniform distribution of microbial communities within the bioreactor often occurs, leading to unstable biological performance [15-18].

The introduction of complex methanogenic microbial populations-responsible for methane formation-into an organic substrate requires adherence to stringent technological parameters within the anaerobic environment. These parameters include:

* continuous and uniform mixing of biomass within the bioreactor;
* maintenance of stable temperature regimes appropriate for the anaerobic process;
* regulation of pH levels within the optimal range of 6.5–7.5;
* moderation of volatile fatty acid (VFA) concentrations;
* preservation of nutrient and compositional balance of the biomass;
* controlled moisture content of organic feedstock to ensure continuous and stable bioreactor operation.

Although more than 3.6 million methanogenic species are known, the aforementioned parameters remain decisive for maintaining the stability of anaerobic digestion, enhancing methanogenic efficiency, and maximizing biogas production [19–27].

**OBJECT OF STUDY**

The diversity of methanogenic microorganisms participating in methanogenesis demonstrates that the process is influenced by the physicochemical characteristics of the medium, anthropogenic factors, operational intensity, and the physical state of the organic substrates involved. Regardless of the bioreactor’s scale, the inherent variability of anaerobic processes and the differing dynamics of methanogenesis under natural or artificially sustained anaerobic conditions necessitate proper adaptation of methanogens to the specific operational environment.

Findings from our experiments [25–34], supported by extensive literature analysis, indicate that the efficiency of anaerobic digestion is strongly dependent on the degree of pretreatment applied to organic waste prior to its introduction into the bioreactor [35–40]. A commonly suggested approach in previous studies involves preheating the biomass according to the required thermal regime of anaerobic fermentation before loading it into the system [41–44].

However, a significant drawback of thermal pretreatment is the sharp reduction in dissolved oxygen within the raw material, which consequently leads to a notable decrease in biogas yield [45]

Experimental and theoretical findings indicate that the application of electrical energy during anaerobic digestion induces significant changes in the elemental composition and concentration of organic waste, similar to the effects produced by other forms of energy input. Under these conditions, the microbial interactions among methanogenic bacteria are enhanced, increasing the adhesive properties of their cell surfaces and thereby exerting a proportional influence on the amount of biogas released from the biomass. This phenomenon represents one of the primary determinants of both the quality and quantity of processes occurring within bioreactors [2,11,12,46–52]. Such transformations ultimately improve the overall efficiency of anaerobic digestion and contribute to increased productivity. At the same time, they highlight the need to scientifically substantiate the technological parameters of biogas systems and to determine the optimal operational conditions for anaerobic processes.

In developing a technology for the preliminary treatment of organic waste using pulsed electrical discharges—and in designing a device capable of implementing this approach—several key considerations were taken into account. These include: the feasibility of conducting pulsed-electrical processing of organic waste within a single vessel, and the necessity of establishing optimal values for the primary parameters governing retention time during pretreatment. These parameters must be identified based on their influence on biogas yield and the production of organic fertilizer.

In practical applications, it is common to cultivate methane-producing bacteria under controlled artificial conditions prior to loading biomass into bioreactors, after which the cultivated cultures are introduced into the reactor environment [53–62]. Analysis of such approaches indicates that they are not economically efficient and often require a high level of technical expertise.

During the course of our experiments, anaerobic bacteria were cultivated under isolated conditions and subsequently loaded in specific portions into a multifunctional apparatus (Figure 1). Under these conditions, an intensified growth of microflora involved in methane fermentation was observed [28–37]. This suggests that optimizing the initial incubation of anaerobic bacteria through exposure to pulsed electric current is an important factor in enhancing fermentation performance [33].

A large number of methanogenic bacteria belonging to different taxonomic groups can be isolated in a universal medium. In many cases, such methanogens are classified as facultative anaerobes. Studies of these isolated strains by numerous researchers [34–42] have led to the conclusion that nine major bacterial groups participate either sporadically or continuously in methane fermentation under these conditions. The core representatives of these groups are typically referred to as putrefactive microorganisms.

In microbiology, species such as Pseudomonas fluorescens, Bacillus putrificus, and Bacillus subtilis have been extensively studied. Pseudomonas fluorescens and Bacillus putrificus, in particular, are classified as facultative anaerobes—microorganisms capable of developing in both oxygen-rich and oxygen-depleted environments [49–58].



**FIGURE 1.** Multifunctional laboratory unit for biogas and organic fertilizer production — component list: 1. Bioreactor (main digestion vessel); 2. Bio-fertilizer vessel (digestate collection/processing tank); 3. Feed/inflow pipe; 4. Mixing paddles (agitator arms); 5. Primary manure processing vessel; 6. Gas filter and meter (gas purification and flow/volume measurement); 7. Loading port (inlet sleeve); 8. Compressor; 9. Secondary manure processing vessel (secondary treatment stage); 10. Computerized control panel (PC-based control and monitoring console)

Methanogenic bacteria play a central role in methane fermentation, producing a substantial proportion of the methane generated during the process. In contrast, Bacillus subtilis is classified as an aerobic microorganism and primarily participates during the initial stages of anaerobic degradation. However, this approach does not allow for the quantitative assessment of cell growth intensity, as the bacteria can only be detected visually. Methanogenic microorganisms are generally characterized by limited motility and develop within a confined anaerobic environment [17–22].

In the experiments, organic waste was first prepared by adjusting its moisture content and particle size. The material was then subjected to a high-intensity pulsed electric field, during which the number of electrical pulses was precisely controlled. Since the magnitude and duration of these pulses constitute key operational parameters, the current intensity was regulated using a rheostat.

From a scientific perspective, the application of pulsed electric fields (PEF) during anaerobic digestion enhances electroporation of microbial cell membranes, thereby increasing the extent of biological substrate degradation. This accelerates the hydrolysis phase and increases the availability of biologically active organic compounds for anaerobic bacteria. High-voltage, short-duration pulses produced by PEF help regulate microbial structure, improve fermentation stability, and ultimately increase total yields of methane and intermediate products such as organic acids. In practical applications, the use of PEF in anaerobic fermentation offers economic advantages through energy savings and reduced processing time [54–66]. Since PEF modifies the internal structure of the substrate, it is particularly effective for solid biomass, where biogas yields can be improved by 10–25%. Nevertheless, the high capital cost of the equipment and the need for precise parameter optimization present limitations in industrial settings. Despite these constraints, our experiments indicate that PEF is emerging as a strategically significant auxiliary technology with high efficiency in anaerobic biotechnology.

**RESEARCH RESULTS**

The findings demonstrate that, rather than cultivating methanogens separately, it is more advantageous to reproduce in dedicated reactors the environmental conditions present in continuously operating anaerobic systems. In other words, methanogenic consortia should be grown in the same substrate and conditions to which they will ultimately be exposed. Numerous studies, including our own experiments, confirm that separately cultivated methanogens provide limited economic benefit when introduced into anaerobic digestion.

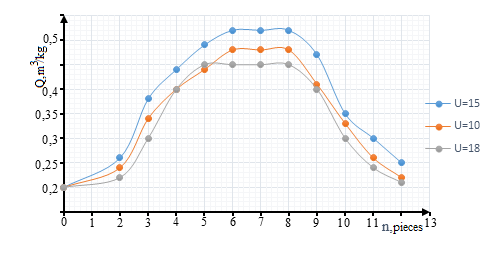
Moreover, our results show that pretreating the substrate with high-frequency electric pulses before loading it into the bioreactor can double biogas production. To enhance the activity of methanogenic bacteria and increase biogas yield per unit working volume of the reactor, we selected several types of organic waste typical for local climatic conditions, including cattle manure, poultry waste, and greenhouse residues.

Experiments were conducted using a device operating according to the schematic diagram provided. Because full reactor start-up (i.e., complete microbial adaptation) requires an extended period, the initial substrate load was weighed accurately using a scale with ±0.01 kg precision. Each day, 10% of the working volume of the bioreactor was introduced. Vacuum conditions were maintained inside the reactor at a pressure below atmospheric level [21,29–32].

For the initial trials, a substrate composed of 85% cattle manure diluted with tap water to a final moisture content of 94% was prepared. After achieving full adaptation of methanogenic bacteria (45 days), the first series of experiments was initiated according to the experimental program. Pulsed high-voltage currents not exceeding 15 mA were applied at voltage levels of 1.3 kV, 3.3 kV, 5 kV, 15 kV, and 25 kV. Each voltage setting was applied for 10 to 30 seconds (Figure 2).

In the experimental laboratory setup, it was observed that when different numbers of pulsed discharges were applied to the daily load of organic waste, the volume of biogas generated per effective volume of the bioreactor reached its maximum at treatment voltages ranging from 12 to 16 kV. This outcome indicates that, under these conditions, the pulsed discharge effectively enhances the disintegration of solid fractions within the biomass while simultaneously maintaining a sufficient concentration of microorganisms in the substrate. As a result, optimal environmental conditions are created for the growth and metabolic activity of anaerobic bacteria.

However, when the discharge voltage exceeded 16 kV, a decline in biogas yield was recorded. This reduction is attributed to the detrimental effect of excessively high-voltage pulses, which begin to damage or eliminate beneficial microbial populations within the substrate. Consequently, the reduced microbial activity leads to a lower rate of biomass degradation and, therefore, a decrease in the volume of biogas generated per unit of the bioreactor’s effective volume.



**FIGURE 2.**Dependence of biogas yield from the bioreactor on the number of pulsed discharges at different treatment voltages (capacitance C = 0.7 µF).

According to the results illustrated in Figure 2, at a fixed discharge voltage, an increase in the number of pulses leads to a proportional rise in the biogas yield from the bioreactor. However, when the pulse number exceeds nine, the amount of biogas produced begins to decrease. This decline is primarily attributed to the inactivation and subsequent death of microorganisms within the biomass, caused by excessive pulsed electrical stress. Adjusting the pulse frequency enables modification of the structural properties of the aqueous organic substrate, variation in activation energy, and regulation of biochemical reactions. Nevertheless, when more than nine pulses are applied, the pH of the substrate increases, creating unfavorable conditions for anaerobic microbial activity.

During the initial phase of experimentation, a low electric impulse of 5 kV was applied. The biomass loaded into the bioreactor was pre-processed to a particle size of approximately 2 mm and adjusted to a moisture content of 92–94% ±2%. The pulsed current was introduced within intervals ranging from 1 to 6 seconds. Further experiments were conducted by varying the discharge voltage from 5 to 25 kV. Based on these investigations, the biogas yield per effective volume of the bioreactor was plotted in graphical form.

When the discharge voltage exceeded 16 kV, a notable decrease in biogas production was observed, indicating that the elevated pulse energy leads to the death of beneficial microorganisms in the substrate. As microbial activity declines, the rate of biomass decomposition is reduced, resulting in lower biogas output.

Experimental observations further demonstrated that increasing the capacitance of the discharge-forming capacitor initially enhances the biogas yield. However, when the capacitance exceeds 1.1 µF, the biogas production begins to decline. This is explained by the rise in pulse discharge energy, which increases the amount of energy absorbed by the biomass and exerts detrimental effects on microbial cells. Higher energy input may cause cellular destruction, gas ionization, and disruptions in metabolic processes essential for anaerobic digestion.

Overall, the experimental studies confirm that high-voltage pulsed discharge treatment of the aqueous organic substrate alters its structural composition, initiates chain reactions involving free radicals, and enhances the breakdown of organic components. This effect simultaneously stimulates methanogenic microorganisms, promoting their growth and metabolic activity during anaerobic digestion.

Investigations on substrate structural modification show that identifying the optimal parameters of pulsed high-voltage treatment can significantly accelerate fermentation, activate microbial communities, and enhance biogas production. Since electron transfer processes play a central role in biochemical reactions, controlling electron flux within the substrate offers a potential pathway to optimize biospecific synthesis of active particles that enhance biogas yield.

The conducted experimental studies made it possible to determine the permissible limits of electrical pulsed treatment. Exceeding these limits results in microbial inactivation and reduced biogas output. Future research should therefore focus on identifying the optimal pre-treatment parameters of pulsed electrical discharge to be applied to the biomass prior to its introduction into the bioreactor.

**CONCLUSION**

In summary, one of the key factors influencing the increase in biogas yield per effective volume of the bioreactor is the application of pulsed electrical discharge during the biomass loading stage. The experimental results demonstrate that the optimal treatment parameters include a discharge voltage of U = 12 kV, a pulse number of n = 6, and a capacitor capacitance within C = 1.1 µF. Lower-intensity pulsed currents exhibit a weaker stimulatory effect on methanogenic microorganisms present in organic waste materials. Therefore, considering local climatic and operational conditions, applying pulsed electrical pre-treatment to organic waste prior to loading into the bioreactor can be regarded as one of the most cost-effective strategies for enhancing anaerobic digestion efficiency.

During anaerobic digestion, the pulsed electric field induces electroporation of cellular structures, thereby accelerating the hydrolysis stage and increasing the availability of active organic substrates required for methanogenesis. International studies also confirm that pulsed electric field treatment can enhance biogas productivity by 10–25%, shorten fermentation time, and significantly improve the degradability of recalcitrant lignocellulosic biomass.

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