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Impact of cavitation destruction of cattle manure experiments on increasing methane yield in biogas and improving digestate quality in bioreactors under control system operating parameters

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Abstract

This study aims to evaluate the effectiveness of a pilot-scale Raw Material Processing Unit (RMPU) that integrates hydrodynamic cavitation (HC), grinding, and heating to enhance anaerobic digestion (AD) of cattle manure and improve digestate nutrient recovery. Cavitation dynamics were modeled using the Rayleigh–Plesset equation, Bernoulli's principle, and mass/energy balances to identify optimal parameters ($\sigma \approx 0.42$ at 0.4–0.5 bar). A PLC-based control system was developed for real-time regulation of pressure, flow, and temperature. Semi-industrial experiments at the "Akzhar" farm (Kazakhstan) evaluated biogas yield, methane content, and digestate nitrogen, phosphorus, and potassium (NPK) concentrations before and after pretreatment. The RMPU increased biogas yield by 27.5 % (417 vs. 327 mL/g COD), methane content by 5.5 % (64.7 % vs. 59.2 %), and digestate NPK availability by 38–43 %. The time to peak methanogenesis was reduced by 37.5 % (5 vs. 8 days). The process remained stable with consistent pH and volatile fatty acid levels.Model-guided HC pretreatment, combined with automated control, reliably enhances AD efficiency and digestate agronomic value under farm-scale conditions.The compact RMPU can be integrated into existing agricultural biogas plants without major redesign, improving energy efficiency, reducing digestion time, and producing nutrient-enriched digestate suitable for sustainable and organic farming systems.

Keywords: Anaerobic digestion, Animal waste, Automation, Biogas, Cattle manure, Digestate, Hydrodynamic cavitation, Mathematical modeling, Raw material processing unit (RMPU).

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1. Introduction

The agro-industrial sector faces increasing pressure in the field of sustainable cattle manure management, driven by the growing livestock population, stricter environmental regulations, and the necessity to transition toward a circular bioeconomy model [1]. It is estimated that more than 4 billion tons of livestock waste are generated worldwide annually, with cattle accounting for a significant share. In particular, volumes in China reach this order of magnitude [2] while the global total volume of fecal biomass (animals and humans) was about 4.3 billion tons, with animal waste exceeding human waste by a factor of five [3]. Moreover, cattle alone are responsible for approximately 3.4 billion dry tons of manure annually [4]. Improper manure handling results in greenhouse gas emissions, eutrophication of water bodies, and losses of valuable macronutrients—nitrogen, phosphorus, and potassium [5].

Traditional waste management practices—such as open storage, landfilling, and uncontrolled composting—are increasingly recognized as unsustainable due to their high carbon footprint, odor emissions, and risk of pathogen dissemination [6]. In response, regulatory frameworks worldwide are tightening restrictions on manure handling, compelling the agricultural sector to adopt circular bioeconomy models that prioritize resource recovery and energy efficiency [7].

One of the promising sustainable technologies for manure valorization is anaerobic digestion (AD) of cattle manure which enables to convert livestock waste into biogas and nutrient-rich digestate [8]. Despite the sustainability of AD, the process is limited by the low biodegradability of complex organic compounds such as cellulose, lignin, and chitin, which slows down the hydrolysis stage and reduces the methane potential of the substrate [9, 10]. To overcome these limitations, various pretreatment methods have been investigated, including thermal, alkaline, ultrasonic, and mechanical destruction [11]. Although these approaches improve substrate accessibility for methanogenic microorganisms, they are typically energy-intensive, costly, and difficult to scale for farm-level applications.

In recent years, hydrodynamic cavitation (HC) has attracted increasing attention as an emerging and relatively low-cost manure pretreatment alternative to mechanical destruction [12]. The collapse of cavitation bubbles generates localized zones of high temperature and pressure, which facilitate the breakdown of cell structures and the solubilization of organic compounds [13]. Several studies have demonstrated that HC significantly accelerates the hydrolysis phase and improves the efficiency of Abdrashitov, et al. [14] For instance, Dębowski, et al. [15] showed that HC pretreatment of cattle manure increased biogas yield by 28–34% and volatile fatty acids (VFA) concentration by 45%, indicating accelerated enzymatic activity. Similar results were reported by Langone, et al. [16] in the co-digestion of manure with lignocellulosic biomass. Beyond volume enhancement, HC also improves the qualitative composition of biogas. Methane content in the gas mixture increases from 58–60% to 64–68%, thereby enhancing its energy value [17]. In addition, the agronomic properties of the digestate are improved: concentrations of ammonium nitrogen, soluble phosphorus, and potassium increase, making it a more effective organic fertilizer [18].

Despite aforementioned encouraging results, most studies have been conducted under laboratory conditions that do not adequately reflect the complexity and variability of industrial farm systems [19]. Furthermore, many studies lack detailed mathematical descriptions of cavitation processes, which limits reproducibility, scalability, and opportunities for automation. In many installations, parameters such as pressure, flow rate, and temperature are still manually adjusted, reducing process reliability and energy efficiency, particularly when transitioning to continuous operation.

To address these shortcomings, modern cavitation systems must incorporate intelligent automation and robust mathematical models. Application of the Rayleigh–Plesset equation, Bernoulli's principle, and mass and energy balances enables precise control of bubble collapse dynamics and substrate disintegration rates. Integrating these models into the logical control structure of the raw material processing unit (RMPU) ensures adaptive real-time parameter adjustment, reduces energy consumption, and enhances the stability of both biogas and digestate quality [20]. Thus, the development of automated, model-driven cavitation systems adapted to farm-scale conditions is a crucial step toward sustainable and efficient manure management.

This study introduces several innovations compared to previously published works:

- Unlike most laboratory-scale experiments, the developed RMPU was tested under semi-industrial conditions at the operating «Akzhar» farm in Kazakhstan, using real cattle manure with varying composition;
- An automated PLC-based control system was implemented, enabling rapid adjustment of process parameters;

- Cavitation process modeling was conducted using the Rayleigh–Plesset equation to optimize operational conditions;
- For the first time in a comprehensive analysis, not only biogas yield but also nutrient recovery (N, P, K) in digestate was evaluated, expanding the technological applicability.

These scientific and technological solutions contribute to bridging the gap between laboratory research and industrial implementation of cavitation-enhanced manure treatment systems, targeting energy efficiency and sustainability.

The primary aim of this research is to bridge the gap between laboratory studies and industrial-scale implementation of cavitation-enhanced anaerobic digestion, thereby ensuring complete manure utilization, improving the quality of organic fertilizer, and enhancing the energy efficiency of the process.

2. Materials and Methods

2.1. Description of the Technological Process of the Raw Material Processing Unit

Figure 1 presents the technological scheme of the cattle manure processing unit, designed for subsequent anaerobic digestion. The system includes stages of mechanical preparation and hydrodynamic activation of the substrate.

The raw material flow from the cattle farm enters a receiving tank for accumulation. Using a fecal pump, the manure is transported to a screw shredder, which performs primary mechanical grinding to fractions of 10–20 mm. The material is then directed to a blade shredder for further grinding into a finer and more uniform fraction [16].

Next, the substrate enters a preparation tank, where a temperature range of 15–20°C is maintained. This temperature preserves microbiological activity without triggering premature fermentation. The tank is equipped with temperature and level sensors, enabling automated control of the preparation mode.

Upon reaching the specified parameters, three sequentially activated units are engaged:

- A macerator, ensuring circulation and dispersion of the mass;
- A gerotor pump, generating the required delivery pressure;
- A cavitation disperser (8), where high-pressure conditions (up to 6 bar) in a nozzle constriction (e.g., Venturi) create hydrodynamic cavitation.

As a result, the cavitation zone intensifies the breakdown of cell walls and the destruction of complex organic compounds, enhancing the substrate's bioavailability for methanogenic bacteria [21].

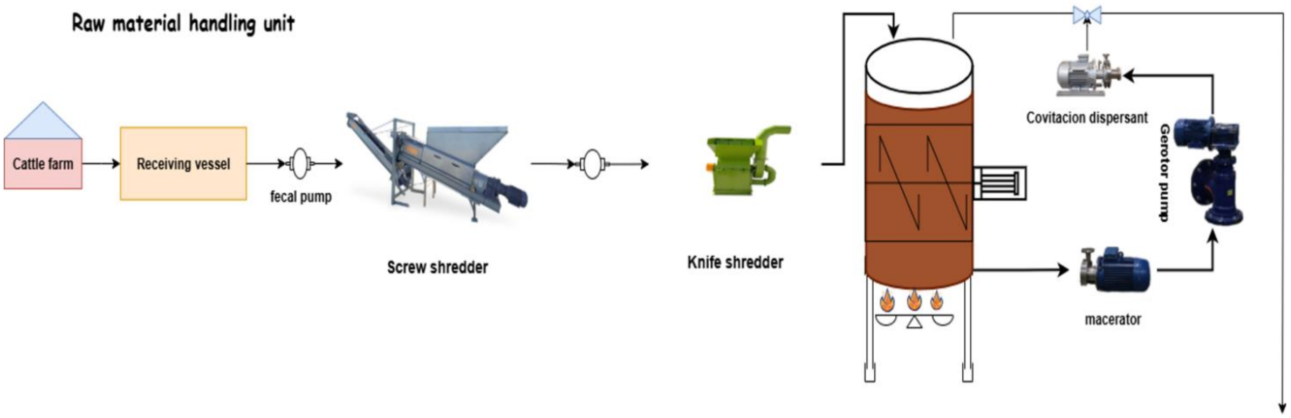

Figure 1.
Technological scheme of the raw material processing unit using screw and knife shredders, heating and cavitation dispersant.

2.2. Principle of Operation of the Cavitation Unit

Hydrodynamic cavitation occurs as biomass flows through a venturi nozzle, where a sharp pressure drop forms cavitation bubbles. Their collapse generates micro-explosions with temperatures up to 5000 K and pressures up to 100 MPa [15]. The flow velocity in the nozzle is 12–15 m/s, and the cavitation number is calculated as Kumar and Brennen [22] (Equation 1):

$$\sigma = \frac{P_{\text{in}} - P_v}{\frac{1}{2}\rho v^2} \quad (1)$$

Where: σ — cavitation number, P_{in} — inlet pressure, P_v — vapor pressure of the liquid, ρ — fluid density, v — flow velocity.

For effective cavitation: $\sigma < 1$. In this system, $\sigma = 0.42$ was used under 4.3 bar pressure and 45 °C.

2.3. Mathematical Modeling of Cavitation Bubble

The dynamics of the cavitation bubble radius $R(t)$ were modeled using the Rayleigh–Plesset equation [23] (Equation 2):

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho}\left(P_g-P_\infty-\frac{2\sigma_s}{R}-\frac{4\mu\dot{R}}{R}\right) \quad (2)$$

- $R(t)$ — bubble radius (m),
- $\dot{R},\ddot{R}$ — velocity and acceleration of radius change (m/s and m/s²),
- $\rho=1000\,\text{kg/m}^3$ — liquid density,
- $\mu=1.002\cdot10^{-3}$ Pa·s — viscosity,
- $\sigma_s=0.072$ N/m — water surface tension,
- P_g — pressure inside the bubble, given as adiabatically compressible gas (Equation 3):

$$P_g(R)=P_0\left(\frac{R_0}{R}\right)^{3\gamma} \quad (3)$$

- P_∞ — pressure in the fluid away from the bubble.

The modeling was carried out in the MATLAB environment using the built-in ode45 solver, which is based on the Runge–Kutta method of 4th–5th order. The Rayleigh–Plesset equation was solved numerically using the initial conditions:
- initial bubble radius: $R_0=10^{-5}\,m$,
- initial speed: $\dot{R}(0)=0$.

2.4. Results of numerical modeling.

With a fluid pressure of $P_\infty=0.4$ bar . The obtained results showed that:
- The bubble radius reached a maximum value of $R_{\max}\approx 120\,\mu$m;
- Collapse occurred within$\approx 38\,\mu$s;
- Maximum collapse velocity was tens of m/s, generating a shock wave.

The graph of the dependence of the bubble radius on time is shown in Figure 2:

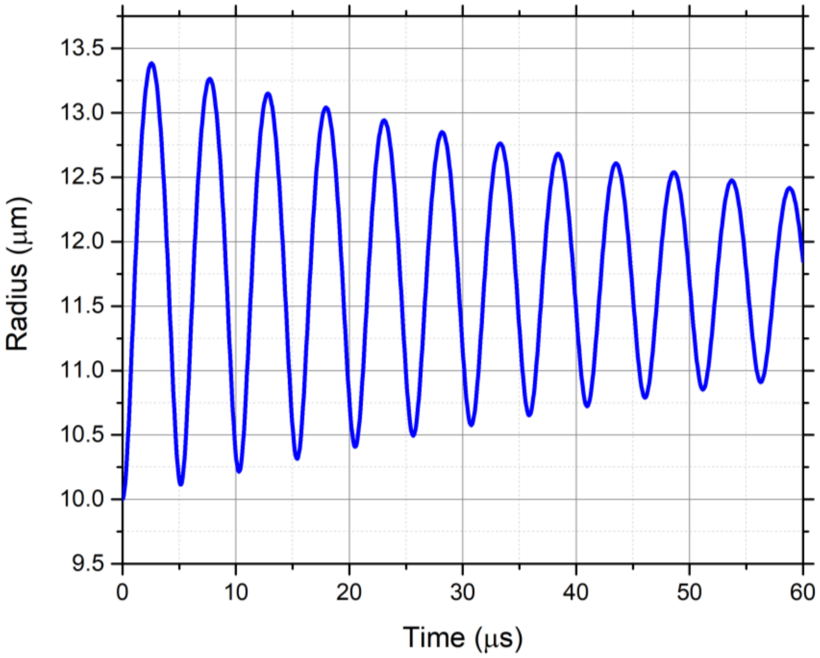

Figure 2.
Variation of the cavitation bubble radius $R\,(t)$ over time, calculated from the Rayleigh-Plesset equation.

The program model is developed using Matlab code which can be found Supplementary Material.

2.5. Energy and Material Balance Equations

Basic equations were used to describe the operation of the system:
- Bernoulli's equation for an incompressible fluid between points 1 and 2 (Equation 4):

$$P_1+\frac{1}{2}\rho v_1^2+\rho g h_1=P_2+\frac{1}{2}\rho v_2^2+\rho g h_2+\Delta P_{\text{losses.}} \quad (4)$$

- Weight balance (Eq. 5):

$$\dot{m}_{\text{in}}=\dot{m}_{out} \quad (5)$$

- Energy balance (Eq. 6):

$$Q_{\text{external}} + W_{\text{pump}} = \Delta H_{\text{cavitations}} + Q_{\text{heating}} \tag{6}$$

Energy and heat losses were compensated by regulating the pump and heaters through the controller.

2.6. Experimental Methodology

The experiments utilized cattle manure with a moisture content of 85–88%, processed at a flow rate of 150 L/h for 40 minutes, under an inlet pressure of 4.2–4.8 bar. The biomass composition, including chemical oxygen demand (COD), pH, dry residue, and macroelements (nitrogen, phosphorus, potassium), was analyzed before and after treatment.

The temperature measurement error using PT100 sensors was ±0.2°C, pressure measurement error was ±0.05 bar (using verified digital sensors), and macroelement content measurement error was ±5% (based on standard laboratory methods). All measuring instruments underwent preliminary calibration: temperature sensors were calibrated in a water bath with a reference thermometer, and flow meters were calibrated using a measuring tank. Verification was conducted in accordance with factory instructions and standards GOST R 8.585–2001, GOST R 8.781–2011, GOST 26713–85, ISO 60751:2022, ISO 5315:1984, and ISO 7497:1984.

All process stages are controlled by an automated control system (ACS) based on a programmable logic controller (PLC), integrated with an operator SCADA system via the RS-485 interface (Figure 3). This ensures precise maintenance of process parameters and seamless integration into the overall biogas plant control loop.

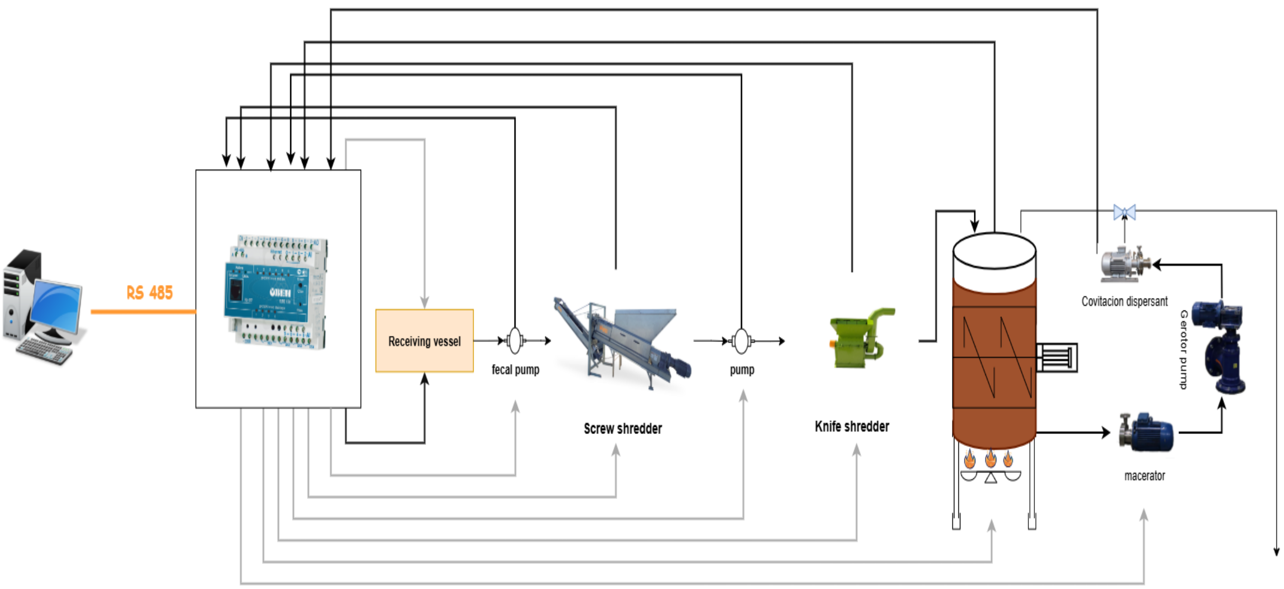

Figure 3.
Structural and functional scheme of the automated cavitation destruction system for cattle manure.

To automate the preparation process of cattle bedding manure prior to anaerobic digestion, the OWEN PLC150 programmable logic controller is used, integrated with the SCADA Trace Mode visualization system via the RS-485 interface using the Modbus RTU protocol. It manages the entire process, from feedstock supply to cavitation degradation, controlling levels, temperatures, and actuator coordination. Signals from level sensors trigger the fecal pump, while analog inputs from temperature sensors regulate heating and destructive units. Control signals are output via discrete outputs to actuators through relays.

The system includes:

- Fecal pump,
- Screw shredder,
- Knife shredder,
- Macerator,
- Gerotor pump,
- Cavitation dispersant.

The control algorithm follows a sequential logic:

1. The receiving tank fills with manure.
2. Upon reaching the set level (DI0), the fecal pump (DO1) activates, feeding the mass to the screw shredder.
3. The screw shredder (DO2) performs primary grinding.
4. The knife shredder (DO3) further reduces particle size.
5. The mixture enters the preparation tank.
6. The heating system (DO4) activates, regulated by analog input AI0.

7. Upon reaching the set temperature, the macerator (DO5), gerotor pump (DO6), and cavitation dispersant (DO7) start sequentially. The receiving tank is filled with manure from the farm.

Each stage is controlled by the PLC, with all parameters displayed and archived in the SCADA Trace Mode system. The operator can set parameters, monitor the status of equipment in real time, and manually start or stop the system. This ensures flexible, adaptable, and reliable management of the manure pre-treatment process, essential for subsequent utilization or methanogenesis.

2.7. Description of the Technological Process for Producing Organic Fertilizer through Processing Livestock Waste

Figure 4 illustrates the technological scheme of a two-stage methane digestion process designed for processing cattle bedding manure, pre-treated in the raw material preparation unit (RMPU). The substrate is fed from the RMPU into the main bioreactor, which includes two temperature zones: an initial psychrophilic stage (15–20°C) and a subsequent mesophilic stage (35–40°C). Internal partitions ensure the sequential passage of biomass, with biogas extracted through upper nozzles. Hot water circuits maintain the specified temperatures in the digestion zones.

After primary fermentation, the partially processed substrate is transferred to a post-digester, where additional recovery of valuable anaerobic digestion products occurs. The resulting digestate undergoes mechanical separation into solid and liquid organic fertilizers. The extracted biogas passes through a purification unit, including desulfurization, drying, and compression stages, before being directed to a gas holder for storage or further energy use.

The entire system is equipped with an automated control and monitoring loop, enabling optimization of process parameters at each stage of bioconversion.

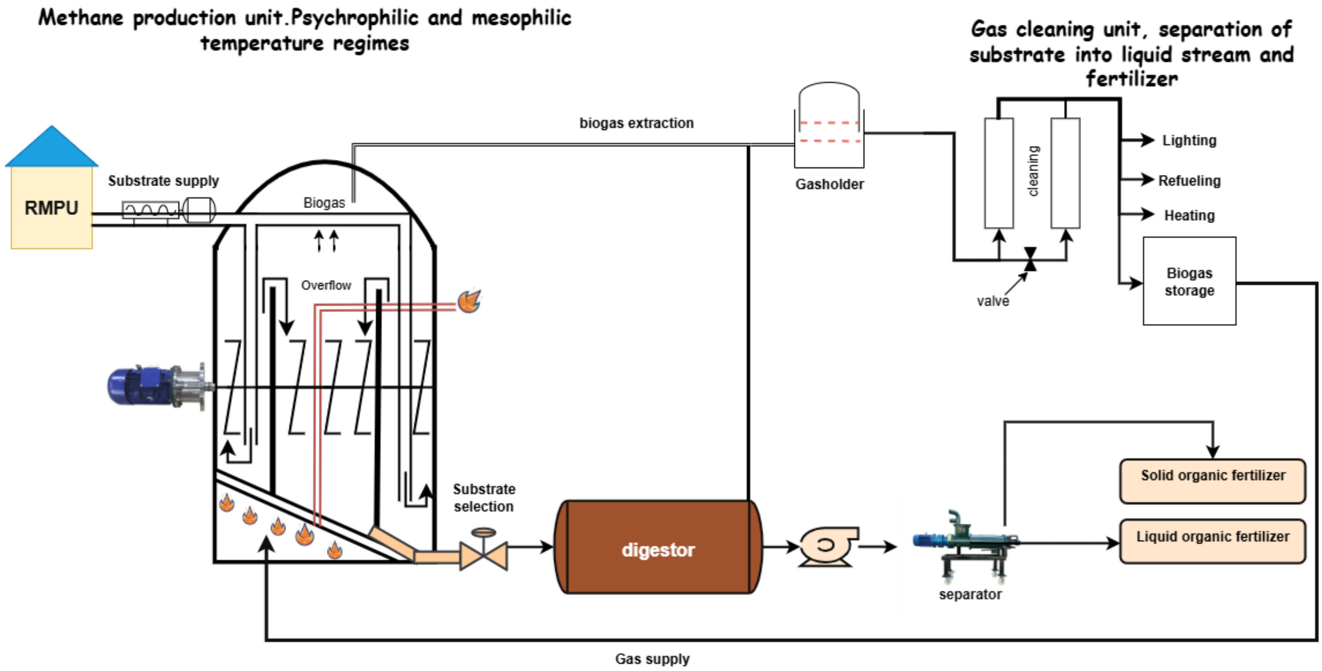

Figure 4.
Functional diagram of the technological process for producing organic fertilizer through the processing of livestock waste.

3. Results

3.1. Modeling the Dynamics of a Cavitation Bubble

The cavitation process was modeled by analyzing the dependence of bubble radius R(t) on external pressure P using the Rayleigh-Plesset equation. The results demonstrated that when the pressure was reduced to 0.4 bar, the bubble radius expanded to 120 μm before undergoing abrupt collapse within 38–42 μs [22] (Figure 5).

Key observations include:

1) At 0.4 bar: Significant bubble expansion (up to 13.4 μm) followed by rapid collapse.
2) At 0.6 bar: Moderate expansion with smaller amplitude and smoother collapse dynamics.
3) At 0.8 bar: Minimal cavitation oscillations, with the bubble radius remaining near its initial value.

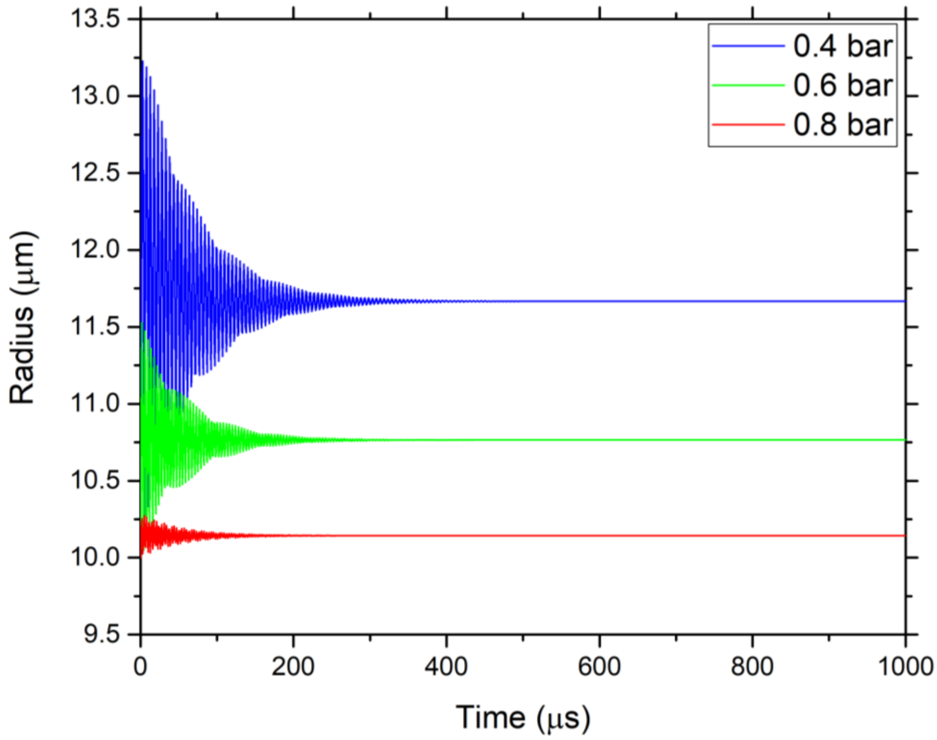

Figure 5.
Time dependence of the cavitation bubble radius at pressures of 0.4, 0.6, 0.8 bar.

The data further indicate that the optimal cavitation regime occurs at P ≈ 0.4–0.5 bar, corresponding to a cavitation number of σ = 0.42

3.2. Automated Control System

To assess the impact of cavitation treatment on the availability of nutrients in cattle bedding manure for microorganisms, real-time monitoring of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) concentrations was conducted before and after treatment using the SCADA Trace Mode platform (Figures 6, 7, 8).

Input parameters are set by the operator via a touchscreen interface. The control algorithm regulates pressure, temperature, flow rate, and processing time. In case of parameter deviations, alarm signals are triggered, and protective shutdown is activated. All data is logged in the SCADA system and stored for analysis.

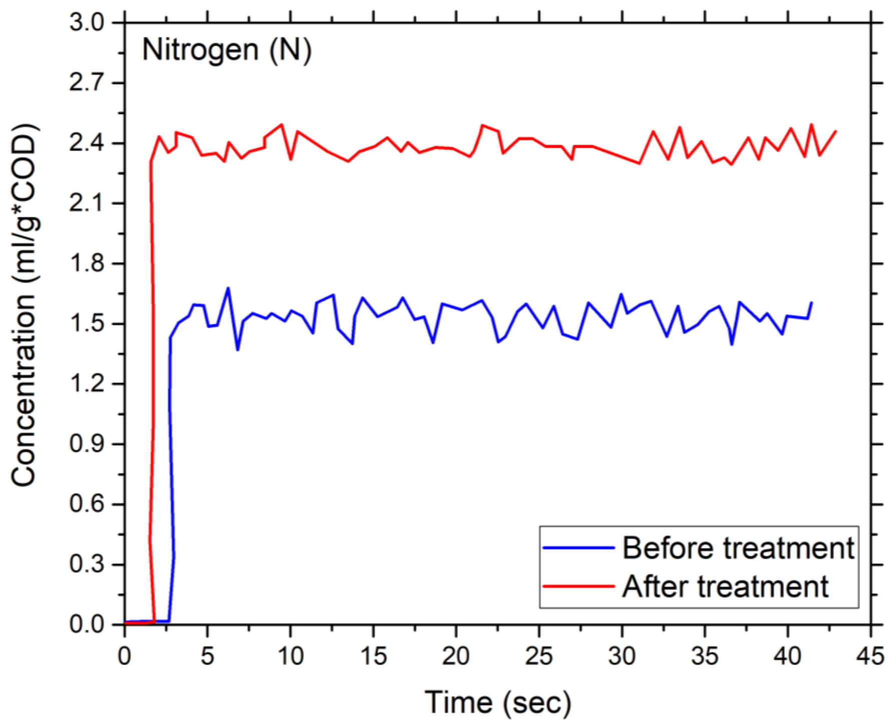

Figure 6.
Variations in nitrogen (N) concentration during cavitation before and after cattle manure treatment (Trace Mode).

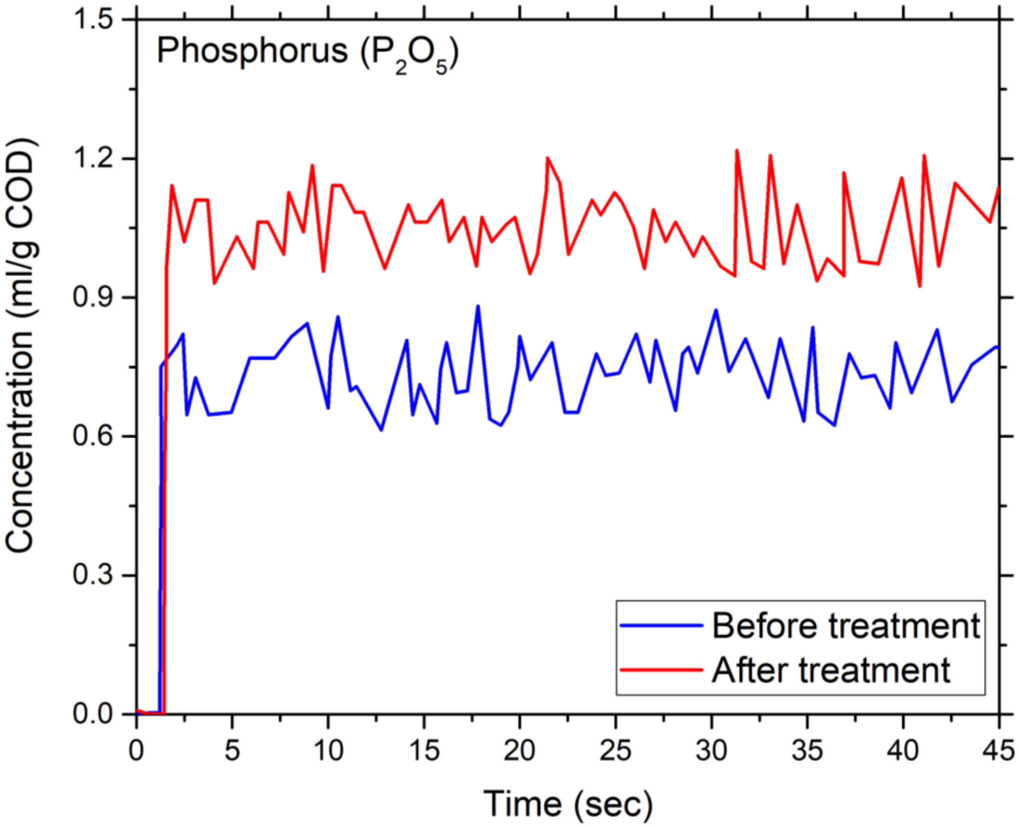

Figure 7.
Variations in Phosphorus (P_2O_5) concentration during cavitation before and after cattle manure treatment (Trace Mode).

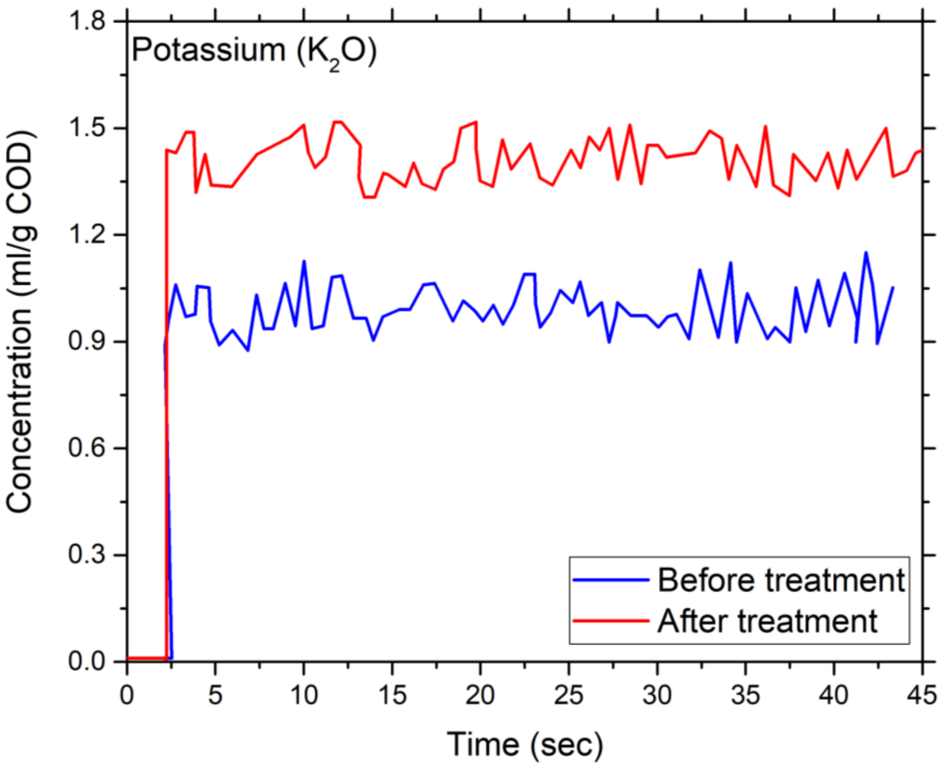

Figure 8.
Variations in Potassium (K_2O) concentration during cavitation before and after treatment of cattle manure (Trace Mode).

Comparative analysis of pre- and post-cavitation biomass revealed substantial increases in bioavailable macronutrients (Table 1): nitrogen rose from 1.62% to 2.24% (+38%), phosphorus from 0.84% to 1.18% (+40%), and potassium from 1.11% to 1.59% (+43%).

Table 1.
Content of available forms of N, P, K in biomass (% of dry weight).

Indicator	**Before processing**	**After processing**	**Growth (%)**
Nitrogen (N)	1.62 %	2.24 %	+38 %
Phosphorus (P_2O_5)	0.84 %	1.18 %	+40 %
Potassium (K_2O)	1.11 %	1.59 %	+43 %

These enhancements directly result from cavitation-induced cell membrane disruption, which converts refractory organic nitrogen and phosphorus into forms readily accessible for microbial metabolism.

3.3. Biogas Yield and Composition

Cavitation pretreatment had a significant effect on biogas yield and quality. The following parameters were observed in the control and experimental groups (with and without RMPU)

- Biogas yield increased from 327 ml/gCOD to 417 ml/gCOD - an increase of 27.5 %.
- CH_4 content increased from 59.2 % to 64.7 %.
- The time to reach the peak of methanogenesis decreased from 8 days to 5 days**.**

The integral evaluation of the process efficiency is summarized in Table 2:

Table 2.
Comparative parameters of anaerobic digestion before and after cavitation destruction.

Parameter	**Without RMPU**	**With RMPU**	**Growth**
Total biogas yield (ml/gCOD)	327	417	+27.5 %
Average CH_4 content (%)	59.2 %	64.7 %	+5.5 %
Time to peak CH_4 (day)	8	5	–37.5 %
Available NPK (total)	3.57 %	5.01 %	+40.3 %

3.4. Process Stability

Based on the results of monitoring pH, temperature and LFA for 14 days, it was found that the experimental group had a more stable acid-alkaline environment (pH 6.8-7.4), with less fluctuation in LFA concentration. This indicates a better buffering capacity and uniform load on methanogenic microflora.

Also, a 16% decrease in residual dry matter was observed in the RMPU group, indicating a deeper degree of organic matter decomposition.

To evaluate the impact of cavitation treatment on the availability of nutrients in cattle bedding manure Haroun, et al. [24], real-time monitoring of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) concentrations was conducted using the SCADA Trace Mode system. The experimental part of the study was carried out at an operational pilot-industrial facility at the “Akzhar” farm (Zhambyl Region, Kazakhstan), where the startup and adjustment of control loops were performed, including temperature regulation, pressure in the cavitation module, and automation of the cavitation destruction process.

The procedure involved calibrating sensors, starting pumping equipment, configuring emergency and operational modes, and visualizing data through the “Trend” module in Trace Mode. The operation of the controller and the operator panel interface is depicted in Figure 9 (left — valve control, right — parameter adjustment on the operator panel).

Figure 9.
Startup of pumping equipment and configuration of emergency and operational modes by the operator.

4. Discussion

The obtained results confirm the high efficiency of cavitation pretreatment as a method of intensifying anaerobic digestion of livestock waste. The observed 27.5% increase in biogas yield, higher methane concentration, and improved digestate composition are consistent with previously published findings. For example, Dębowski, et al. [15] reported a 28–34% increase in biogas yield and accelerated methanogenesis when applying hydrodynamic cavitation to cattle manure. Similar improvements (20–35% yield increase) were documented in studies Kadam, et al. [9] and Szaja, et al. [13] confirming the reproducibility and reliability of the method.

The reduction in methanogenesis time and enhanced gas yield are attributed to cavitation-induced disintegration of cattle manure particles, which disrupts the structure of solid biomass components. This increases the specific surface area of the substrate, thereby facilitating more efficient access of hydrolytic and methanogenic microorganisms to organic compounds [25]. As a result, the AD process is accelerated, leading to more intensive release of gaseous and soluble products. Furthermore, the shorter digestion time reduces the energy required to maintain the thermal regime, thereby lowering operational costs.

Comparison with literature highlights the key advantage of our approach—the integration of an automated control system. Whereas most cavitation-equipped pretreatment units operate under laboratory conditions and require manual adjustment, the proposed Raw Material Processing Unit (RMPU) employs a PLC-based control system, enabling dynamic regulation of pressure, temperature, and flow based on real-time sensor data [26]. This ensures process stability in bioreactors and enhances energy efficiency, particularly when transitioning to continuous operation in farm and agro-industrial environments.

From a biochemical perspective, cavitation intensifies the hydrolytic stage, which is the most limiting step in anaerobic digestion. The disruption of cell walls and release of intracellular contents increases the concentration of soluble compounds available for subsequent acidogenesis and methanogenesis. This effect was evident in our study through the higher volatile fatty acid concentration and accelerated methane accumulation. Additionally, the digestate exhibited a 38–43% increase in nitrogen, phosphorus, and potassium content, significantly enhancing its agronomic value, especially for organic farming.

It is important to note that all process parameters remained stable throughout the experiment. pH values and volatile fatty acid concentrations stayed within acceptable ranges, indicating the absence of inhibitory effects or process disruptions. This demonstrates that the proposed technology can be safely integrated into existing biogas plants without major modifications to the fermentation section.

Several limitations should be noted. First, the experiment was conducted on a pilot-scale installation under operating farm conditions, which may restrict scalability of the results [27]. Second, the influence of seasonal variations in manure composition and feeding regimes was not considered. Additionally, long-term equipment durability under high-pressure and abrasive conditions requires further investigation. The mathematical model is based on ideal assumptions and does not yet account for real hydraulic parameters or the non-Newtonian properties of the substrate.

5. Conclusions

1. The developed automated Raw Material Processing Unit (RMPU), integrating mechanical grinding, hydrodynamic cavitation, homogenization, and heating, demonstrated high efficiency in preparing cattle manure for anaerobic digestion.
2. The application of hydrodynamic cavitation with a cavitation number of $\sigma = 0.42$ resulted in a 27.5% increase in biogas yield and a 37.5% reduction in methanogenesis duration compared to the control without pretreatment.
3. The digestate quality was significantly improved: the content of macronutrients (nitrogen, phosphorus, potassium) increased by 38–43%, enhancing its value as an organic fertilizer, particularly in sustainable and organic farming systems.
4. The PLC-based automated control system ensured process stability, rapid adaptation to variations in substrate properties, and integration into continuous operation.
5. Mathematical modeling based on the Rayleigh–Plesset equation, Bernoulli's principle, and energy balance enabled precise calculation and optimization of cavitation parameters and justified the design choices of the RMPU.
6. The results confirm the scalability of the proposed technology for industrial applications in agricultural and agro-industrial biogas plants with minimal design modifications and without the need to alter bioreactors.
7. Reduced digestion time, coupled with increased gas yield and improved digestate quality, makes this technology competitive in terms of energy efficiency, cost-effectiveness, and environmental-economic sustainability.
8. The obtained findings provide a foundation for the further development of integrated digital solutions (digital twins) and intelligent control systems for optimizing organic waste utilization processes at farm and regional levels.

Promising directions for future research include:

- Integration of cavitation reactors into continuous digestion systems with substrate recirculation;
- Adaptation of cavitation models for non-Newtonian fluids;
- Techno-economic assessments at farm and regional levels;
- Expansion of substrate types through co-digestion with crop residues and food waste;

Life cycle assessment (LCA) to evaluate the environmental sustainability of the technology.

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