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DESIGN OF A CHAOTIC SPEED-CONTROLLED MIXING DEVICE AND EFFICIENCY ANALYSIS IN BIOGASS

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Abstract: This study investigates the impact of chaotic speed-controlled mixing on biogas production efficiency and compares it with conventional fixed-speed mixing. Traditional mixing methods, often operated at fixed speeds or continuous modes, lead to high energy consumption and microbial instability. To address this, a hybrid mixing system combining a helical and propeller shaft was designed to enhance substrate homogenization and biochemical reaction efficiency. A Programmable Logic Controller (PLC) was integrated for automatic process control, while chaotic mixing algorithms, based on Hadley, Halvorsen, Lorenz, and Sprott-A systems, dynamically adjusted the mixing speed to optimize performance. Experiments were conducted at 20°C and 30°C under controlled laboratory conditions. Results showed that chaotic mixing significantly improved methane yield and combustion duration compared to fixed-speed mixing. At 20°C, the Chaotic Sprott-A method produced 18 L/day of methane, compared to 16 L/day with fixed-speed mixing. At 30°C, the Sprott-A method reached 22 L/day, surpassing the 20 L/day of the fixed-speed method. Additionally, combustion duration, an indicator of biogas quality, increased from 740 seconds (fixed-speed) to 829 seconds (Chaotic Sprott-A). These findings confirm that chaotic mixing enhances substrate distribution, improves biochemical reaction efficiency. Chaotic speed-controlled mixing presents a promising alternative for biogas reactors, offering higher methane production.

Keywords: Biogas production, Chaos, Mechanical mixing, Speed control

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1. Introduction

In recent years, the increasing demand for sustainable energy solutions and effective waste management has heightened interest in the design of biogas production devices. Biogas production involves the anaerobic digestion of organic matter into biogas (primarily methane and carbon dioxide) through four fundamental stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Kabeyi and Olanrewaju, 2022). The optimization of biogas production processes is crucial for enhancing economic efficiency and sustainability through advanced design and operational applications (Shapovalov et al., 2023). Energy efficiency in biogas production is another critical component influenced by the mixing methods employed. Mechanical mixers have been shown to significantly impact the energy consumption of reactors. For instance, slow-moving inclined mixers can reduce energy consumption by 70% compared to high-speed submersible mixers while maintaining mixing quality (Lemmer et al., 2013). This finding underscores the necessity of selecting energy-efficient mixer designs to enhance the sustainability of biogas production systems (Spodoba and Zablodskiy, 2021; Gbadeyan et al., 2024). Therefore, determining appropriate mixer types and implementing strategic mixing regimes are key factors that can improve biogas yield and overall system performance.

Various studies have focused on the design of biogas digesters and their adaptation to different contexts. For example, research on household biogas digesters emphasizes the importance of materials used to enhance biogas yield (Rajendran et al., 2012; Obileke et al., 2020; Obileke et al., 2021). Additionally, innovative designs such as portable biogas digesters have been developed for use in rural areas of developing countries. However, the commonly used shaking method in biogas production has been reported to have low efficiency (Sebayuana et al., 2021). A study conducted in Poland on biogas production from pig manure highlighted the importance of desulfurization and feedstock selection in process efficiency (Kapłan et al., 2021). Effective mixing enhances substrate homogeneity, improving mass transfer and ultimately increasing biogas yield. In this context, the impact of different mixer designs on biogas production efficiency has been examined. For example, mechanical mixers (such as paddle and helical ribbon impellers) directly affect the performance of anaerobic digesters (Singh et al., 2021; Singh et al., 2021). The selection of the impeller type, its position within the digester, and its dimensions are critical factors in maximizing energy efficiency and enhancing the biodegradation of organic matter (Mahmoodi-Eshkaftaki and Rahmanian-Koushkaki, 2022).

The optimization of mixing parameters has been shown to increase biogas production. Moreover, comparisons among continuous, semi-continuous, and intermittent mixing strategies have revealed that semi-continuous mixing performs best in enhancing biogas yield and maintaining a more stable environment that supports microbial activity (Kashfi et al., 2021). Chaotic mixing, characterized by irregular and complex flow patterns, has the potential to improve mass transfer and substrate homogenization, which are critical for biogas production. Studies by Boesinger et al. have investigated reactive chaotic flow dynamics in tubular reactors, suggesting that chaotic mixing can increase reaction rates compared to static mixers (Boesinger et al., 2005). Martí-Herrero et al. achieved a 44% increase in biogas production through optimized grid modeling in biogas reactors (Martí-Herrero et al., 2014).

Another significant study on the application of chaotic mixing in biogas production introduced a novel chaotic mixer design based on a delta robot and tested its effectiveness in achieving homogeneity in solid-liquid mixtures (Kalayci et al., 2021). Experimental results demonstrated that more homogeneous mixtures could be obtained in a shorter time compared to conventional mixing methods. Chaotic mixing has been identified as an effective approach for optimizing digestion by enhancing substrate mixing and microbial contact. Furthermore, research on polymer composites has shown that chaotic mixing provides high mixing efficiency while minimizing damage to sensitive components (Tabkhpaz et al., 2015). These principles can also be applied in the context of biogas production.

The potential of chaotic mixing to enhance biogas production is supported by studies investigating the mixing of different organic materials, such as kitchen waste and poultry manure. Research by Mousa indicates that appropriate substrate integration can increase methane production and that chaotic mixing techniques can be beneficial in this process (Mousa et al., 2016). Overall, studies suggest that chaotic mixing can improve substrate homogeneity, reduce energy consumption, and enhance biogas yield.

Integrating the mixing process into an automation system presents a significant innovation that can optimize both energy efficiency and microbial activity in biogas production processes. The literature indicates that mixing operations are typically performed at fixed speeds or in continuous mode, which increases energy consumption and negatively affects microbial stability. This study aims to enhance biogas production efficiency by improving substrate homogeneity through a hybrid mixing shaft design, which incorporates both helical shaft and propeller blades. The semi-continuous mixing strategy ensures sustainable microbial activity while simultaneously reducing unnecessary energy consumption. In this regard, the literature suggests that semi-continuous mixing is more effective in increasing biogas yield compared to fully continuous and intermittent mixing methods. However, existing studies are generally limited to specific speeds and durations and do not focus on the dynamic variation of mixing parameters. In this study, the mixing process is performed at varying speeds in a chaotic manner, facilitating more effective mixing of solid-liquid phases and contributing to the efficiency of biochemical reactions.

Research on chaotic mixing methods has demonstrated that irregular flow patterns improve mass transfer and ensure a more balanced distribution of substrates within the reactor. However, a comprehensive study on the systematic application of chaotic mixing in biogas production is lacking in the literature. This study proposes a hybrid mixer design and a mixing process controlled by variable speeds, aiming to minimize energy consumption while enhancing biogas production efficiency. Thus, an innovative approach is presented to improve the performance of biogas digesters, addressing a significant gap in the literature. In addition various studies have been conducted on remote control and IoT-based data collection systems. These studies are considered to contribute to the more efficient and comprehensive monitoring of the biogas production process (Demirsoy et al., 2024).

The structure of this paper is as follows: Section 2 provides a comprehensive overview of chaos theory and system design elements, followed by a summary of the experimental procedure steps. Section 3 presents the experimental results, including their evaluation and discussion. Finally, Section 4 summarizes the findings and offers recommendations for future research.

2. Materials and Methods

In this section, a general overview of chaos theory will first be presented, followed by a detailed examination of the design and experimental procedure of the chaotic speed-controlled mixing system in biogas production.

2.1. Chaos Theory

Chaos theory is a field of research that examines the dynamics of nonlinear systems and analyzes the mathematical models of complex physical phenomena. The foundations of this theory were first established through Poincaré's work in astronomy and later gained increasing popularity with Lorenz's research in meteorology. Today, chaos theory is utilized across various scientific disciplines for the prediction and control of phenomena, and it is also widely applied in studies exploring the beneficial use of randomness in specific processes (Sarıkaya et al., 2024).

One of the most distinctive characteristics of chaotic systems is their extreme sensitivity to initial conditions. This sensitivity causes small differences in initial states to lead to significant changes in system behavior over time. For example, in a double pendulum system, a slight variation in the position from which the system is released at t=0 can result in a completely different trajectory and oscillations at different frequencies. Due to their sensitivity to initial conditions, such systems exhibit a certain degree of randomness, making their long-term predictability highly limited. Chaotic systems display a unique dynamic structure that can be described as the "order within disorder." In this context, chaos is not entirely a state of disorder but rather a transitional form between order and randomness. In the literature, chaotic systems are generally categorized as one-dimensional chaotic maps and three-dimensional chaotic models. While chaotic maps typically involve discrete-time signals, three-dimensional chaotic models are characterized by continuous-time signals. Systems defined in higher dimensions are referred to as hyperchaotic systems (Hamida El Naser and Karayel, 2024). The mathematical framework provided by chaos theory is not limited to technical fields such as physics and engineering but is increasingly utilized in various disciplines, including economics, biology, ecology, and neuroscience. In this context, studies on the analysis and control of chaotic systems are expected to contribute to enhancing the predictability of these systems and enabling their more efficient management.

In the literature, several widely studied chaotic systems—including the Hadley, Halvorsen, Lorenz, and Sprott-A systems—will be used to control the mixing speed of the developed device. The mathematical models of these chaotic systems are presented in equations 1-4, respectively.

$$\begin{aligned}\dot{x} &= ax - y^2 - z^2 + 2\\ \dot{y} &= xy + bxz - y + 1\\ \dot{z} &= cxy + xz - z\end{aligned} \quad (1)$$

The coefficients of the Hadley mathematical model presented in Equation 1 are $a = -0.25, b = -4, c = 4$ and with the initial conditions defined as $x(0) = 0, y(0) = 0$ and $z(0) = 1.3$.

$$\begin{aligned}\dot{x} &= ax + by + cz - y^2\\ \dot{y} &= ay + bz + cx - z^2\\ \dot{z} &= az + bx + cy - x^2\end{aligned} \quad (2)$$

The coefficients of the Halvorsen mathematical model presented in Equation 2 are $a = -1.27, b = -4, c = -4$ and with the initial conditions defined as $x(0) = -5, y(0) = 0$ and $z(0) = 0$.

$$\begin{aligned}\dot{x} &= a(y - x)\\ \dot{y} &= x(b - z) - y\\ \dot{z} &= xy + cz\end{aligned} \quad (3)$$

The coefficients of the Lorenz mathematical model presented in Equation 3 are $a = 10, b = 28, c = -8/3$ with the initial conditions defined as $x(0) = 0, y(0) = -0.1$ and $z(0) = 9$.

$$\begin{aligned}\dot{x} &= y\\ \dot{y} &= -x + y.z\\ \dot{z} &= 1 - y^2\end{aligned} \quad (4)$$

The initial conditions of the Sprott-A mathematical model presented in Equation 4 are defined as $x(0) = 0, y(0) = 0.5$ and $z(0) = 0$.

Chaotic phase portraits will be applied to the asynchronous motor operating in the frequency range of 0 to 50 Hz and normalized within the range of -25 to +25. The phase portraits of the chaotic system equations presented above are shown in Figure 1 for Hadley, Figure 2 for Halvorsen, Figure 3 for Lorenz, and Figure 4 for Sprott-A.

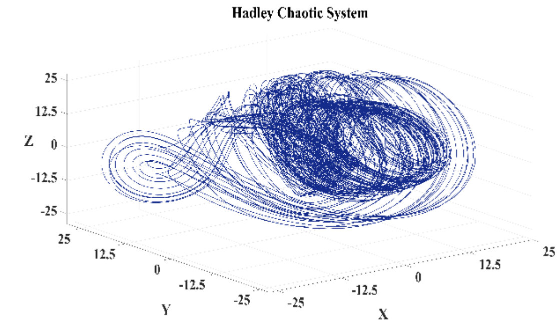

Figure 1. Phase portrait of the hadley chaotic system.

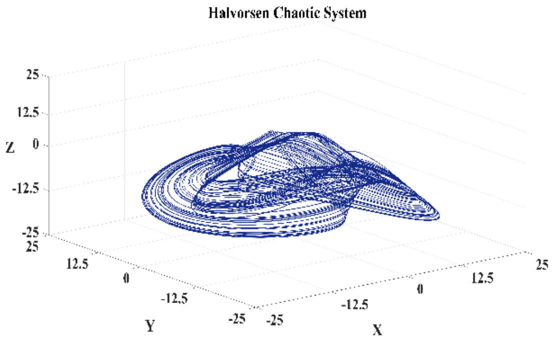

Figure 2. Phase portrait of the halvorsen chaotic system.

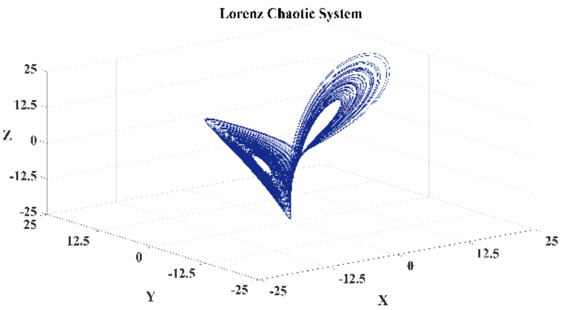

Figure 3. Phase portrait of the lorenz chaotic system.

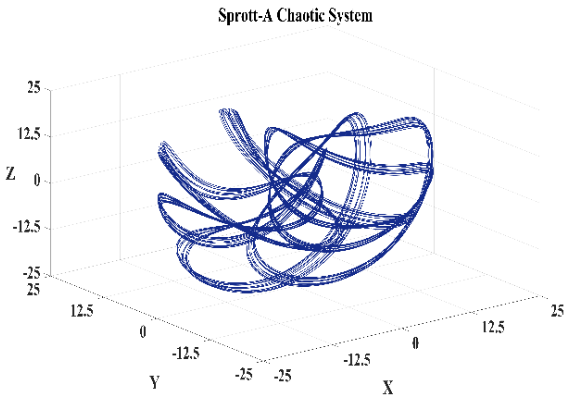

Figure 4. Phase portrait of the sprott-a chaotic system.

2.2. System Design

In this study, an integrated mixing system was designed to ensure optimal mixing conditions in the biogas production process. The system comprises various components to achieve a homogeneous substrate mixture and optimize biochemical processes. A 0.37 kW geared asynchronous motor drives the mixing mechanism, while an inverter-supported control mechanism is integrated to enhance the system's dynamic motion capability and ensure energy efficiency.

Within the mixing tank, a propeller-blade mixer was used to distribute the substrate evenly across all regions. The propeller blades facilitate the mixing process through a circular motion mechanism, ensuring homogeneous distribution of the substrate. A helical mixer extends from the bottom of the tank upwards, serving as a mechanism that enables both substrate transfer and continuous mixing. The helical shaft, driven by the motor, transports the substrate from the lower region to the upper region, thereby increasing mixing efficiency. The helical mixer, coupled to the reducer shaft, supports the vertical movement of the substrate, contributing to the homogenization process, while all system components are integrated to ensure effective mixing. The ability to adjust the mixing speed chaotically allows for dynamic adaptation to different mixing ratios and process requirements. For efficient management of automation processes, the system is integrated with a Programmable Logic Controller (PLC). The PLC enables the automatic control of mixing functions, analysis of process data, and determination of optimal operating parameters based on system conditions.

This system design has been developed to maximize efficiency, ensure energy savings, and achieve homogeneous substrate distribution in the mixing process, offering a comprehensive structure aimed at enhancing the effectiveness of biogas production.

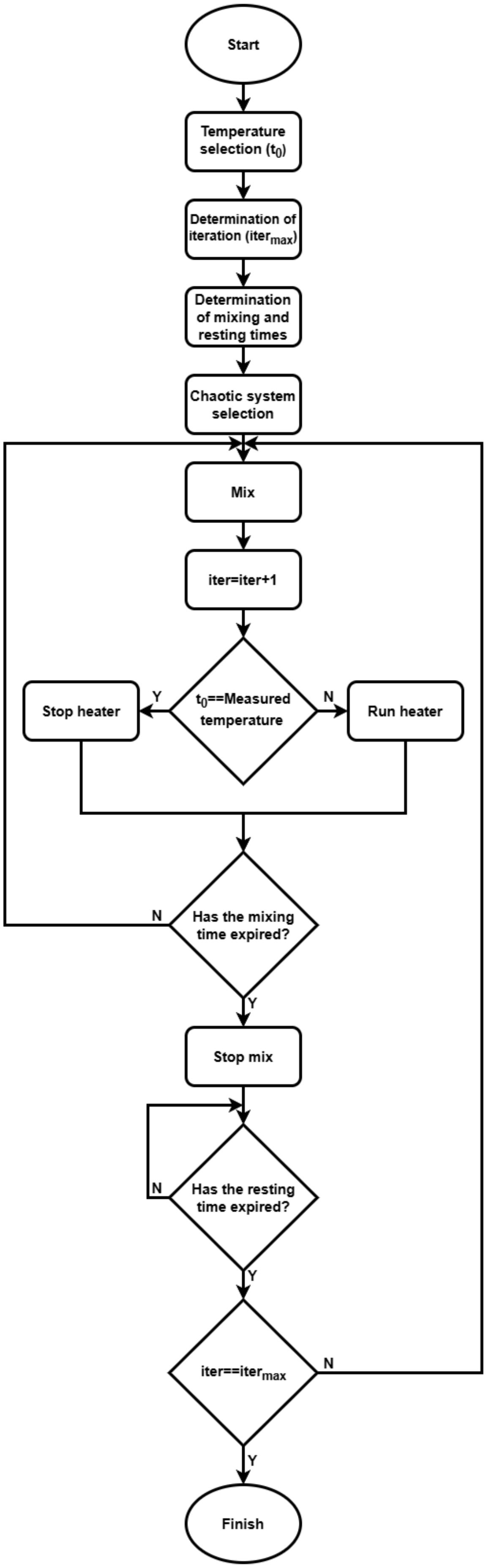

Figure 5. Flowchart.

The flow diagram shown in Figure 5 represents a systematic control algorithm that regulates the mixing and temperature control mechanism in the biogas production process. The process begins with the determination of the initial experimental parameters and continues with mixing-rest cycles, repeating until a predefined number of iterations is reached. During the mixing phase, the system periodically updates the chaotic speed, establishing a dynamic and variable speed profile. Once the mixing duration is completed, the process transitions into the resting phase, and this iterative mechanism continues until the maximum number of iterations is reached. Thus, instead of maintaining a fixed speed profile, a continuously variable and chaotic speed control strategy is implemented, ensuring the adaptive and dynamic nature of the process.

The system first operates by determining the initial temperature (t_0). Subsequently, the maximum number of iterations ($iter_{max}$) to be applied during the experiment, as well as the mixing and resting durations, are defined. Additionally, one of the chaotic mixing systems used in biogas production is selected to determine the mixing method. Once the process is initiated with the defined parameters, the mixing operation is activated, and at the end of each iteration, the iteration counter is incremented. At this stage, the measured temperature (t_{0m}) is compared with the initial temperature. If the measured temperature is equal to the initial temperature, the heater is turned off; however, if the temperature falls below the desired value, the heater is activated. The mixing process continues until the predefined mixing duration is completed, after which the mixer is stopped.

Following this, the resting phase begins, and the system enters standby mode until the predetermined resting duration is completed. Once the resting period ends, the iteration count is checked. If the current iteration count has not yet reached the maximum iteration limit, the process restarts, and the mixing operation is reinitiated. However, if the iteration count reaches the specified maximum value, the process is completed, and the system is terminated.

This structure has been developed to enable the automatic optimization of mixing durations and temperature balance in the biogas production process. The utilization of chaotic systems offers an approach aimed at enhancing the efficiency of biochemical processes and optimizing biogas production performance. Consequently, by dynamically controlling mixing duration, resting duration, and temperature variables, the system ensures the stable execution of the biogas production process.

2.3. Experimental Setup

In this study, experiments were conducted under controlled laboratory conditions to evaluate the effect of different mixing methods on efficiency in the biogas production process. The experimental system consists of a 100-liter mixing tank, an 80-liter manure-water mixture, and a 30-liter storage tank. A 1:1 manure-to-water ratio generally provides a suitable composition for biogas production. The viscosity of this mixture can range between 1 and 50 cP, while the total solids (TS) content varies between 5% and 12%. The mixture exhibits a manageable rheology in terms of mixability; however, its exact physical and chemical parameters should be determined based on the type of manure used and laboratory analyses. The organic substrate utilized in this study consists of cattle manure obtained from a consistent source, ensuring uniformity across all samples. Moreover, all experiments were conducted under comparable initial conditions to maintain experimental reliability and reproducibility. In the study, combustion durations were measured under constant flow rate conditions, and it was determined that an increase in the amount of produced gas extended the combustion duration. This can be explained by the fact that the increase in gas production ensures the continuity of the combustion process, thereby prolonging the combustion duration. Based on the obtained findings, the interaction between combustion duration, gas composition, and efficiency was comprehensively evaluated, and the possible mechanisms explaining this relationship were discussed in detail.

The experimental setup was prepared to contain the 80-liter manure-water mixture and tested under different temperature conditions for each mixing method. The first set of experiments was conducted at 20°C, while the second set was carried out at 30°C, ensuring equal operating conditions across all tests. The mixing process was applied 12 times per day for four days, with each session lasting 11 minutes. At the end of the fourth day, the biogas produced was discharged from the system, and the amount of biogas generated on the fifth day was measured and recorded. Each experimental set was repeated three times to enhance reliability, and the collected data was recorded and analyzed. Figure 6 illustrates the experimental setup.

Figure 6. Experimental setup.

The experimental setup, designed to evaluate the effectiveness of different mixing methods in the biogas production process, is shown in Figure 6. The system's main components are numbered, and the function of each component is structured in a specific order. The electrical panel, labeled as component 1, contains the PLC, inverter, and HMI (Human-Machine Interface) components, which enable system automation. These components are used to regulate system operating parameters, adjust mixing speed, and facilitate data monitoring. The mixing process is carried out by a geared asynchronous motor, labeled as component 2. This motor rotates the mixing shaft, ensuring the homogeneous mixing of the substrate. The mixing tank, where the fermentation process takes place, is labeled as component 3 and is sealed with a silicone-based insulation material to ensure gas tightness. To analyze biogas production under different temperature conditions, the tank is equipped with a heating system. The overall system control and data recording are managed by a computer, labeled as component 4. Integrated with the PLC and other automation components, the computer enables the monitoring and management of all parameters throughout the experimental process. The collection of biogas within the experimental setup is carried out using tanks labeled as components 5 and 6. The initial state of tank 5 contains 30 liters of water, while tank 6 starts empty. Additionally, a discharge outlet located at the lower level of tank 5 is connected to tank 6, which is positioned at a higher elevation. During biogas production, the gas generated in the mixing tank is transferred into tank 5. Over time, the pressure generated by the accumulating biogas in tank 5 alters the water level, causing water to move into tank 6. As a result of this process, compressed biogas accumulates in tank 5, creating a suitable environment for gas storage and measurement. This mechanism is designed to dynamically monitor gas pressure during biogas production and ensure the efficient storage of biogas.

This experimental setup has been developed to examine the impact of mixing methods and temperature variations on the efficiency of biogas production processes. All system components contribute to optimizing biogas production, systematically evaluating the collected data, and determining the effects of various variables on the process.

3. Results and Discussions

This study evaluated the effect of chaotic mixing methods on biogas production efficiency and provided a comparative analysis of these methods against fixed-speed mixing. The experiments were conducted at temperature conditions of 20°C and 30°C, and the amount of biogas produced, along with key performance indicators such as combustion duration, was analyzed. As presented in Table 1, in the experiments conducted at 20°C, it was determined that the fixed-speed mixing method resulted in an average methane production of 16 L/day, whereas chaotic mixing methods improved biogas efficiency to varying degrees. Specifically, the Chaotic Lorenz method achieved a methane production of 17 L/day, while the Chaotic Sprott-A method yielded 18 L/day. This indicates that chaotic mixing methods facilitate more effective substrate homogenization and enhance biochemical processes, thereby increasing methane production. Furthermore, an analysis of combustion duration revealed that biogas obtained through fixed-speed mixing exhibited a combustion time of 555 seconds, whereas the Chaotic Sprott-A method provided the longest combustion duration at 655 seconds. This finding suggests that the Chaotic Sprott-A method may enhance biogas yield.

Table 1. Chaotic mixing and fixed-speed 20°C experiment

Mixing Method	Methane (Day/L)	Burning Time (sec)	Temperature
Chaotic Hadley	16 ± 1	584 ± 16	20^0C
Chaotic Halvorsen	16 ± 1	568 ± 22	20^0C
Chaotic Lorenz	17 ± 1	610 ± 21	20^0C
Chaotic Sprott-A	18 ± 1	655 ± 19	20^0C
Constant Velocity	16 ± 1	555 ± 9	20^0C

The experiments conducted at 30°C, as presented in Table 2, revealed that an increase in temperature enhanced biogas production across all methods. While the fixed-speed mixing method resulted in a methane production of 20 L/day, the Chaotic Hadley and Chaotic Lorenz methods produced 21 L/day, and the Chaotic Sprott-A method achieved 22 L/day. These findings indicate that temperature increases act as a catalyst in biogas production processes and that higher efficiency can be achieved when combined with chaotic mixing methods. In terms of combustion duration, biogas obtained through the fixed-speed mixing method exhibited a combustion time of 740 seconds, whereas biogas produced using the Chaotic Sprott-A method had a significantly longer combustion duration of 829 seconds. Figure 7 presents a graphical representation of the biogas volume and combustion duration for different mixing methods at 20°C, while Figure 8 illustrates the corresponding data for 30°C.

The tolerance margins in the combustion time values presented in Table 1 and Table 2 reflect the data obtained from three independent repetitions conducted for each experimental condition. Although the same environmental and operational parameters were maintained during the experiments, certain variability was observed due to possible uncertainties inherent in the system and measurement errors. In this context, the combustion times specified for each methodology were calculated as the average of three repetitions, while the tolerance margins were determined based on the standard deviation of these measurements. This approach aims to account for potential random variations in the experimental process and enhance the statistical reliability of the obtained results.

Table 2. Chaotic mixing and fixed-speed 30°C experiment

Mixing Method	Methane (Day/L)	Burning Time (sec)	Temperature
Chaotic Hadley	21±1	752±24	30^0C
Chaotic Halvorsen	20±1	738±18	30^0C
Chaotic Lorenz	21±1	745±19	30^0C
Chaotic Sprott-A	22±1	829±16	30^0C
Constant Velocity	20±1	740±13	30^0C

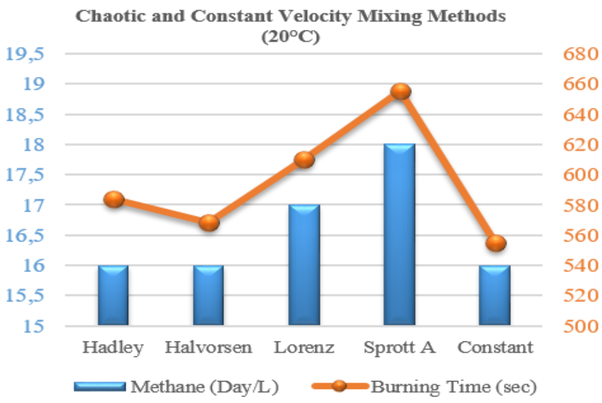

Figure 7. Comparison of methane gas production and combustion duration in 20^0C chaotic and constant speed mixing methods.

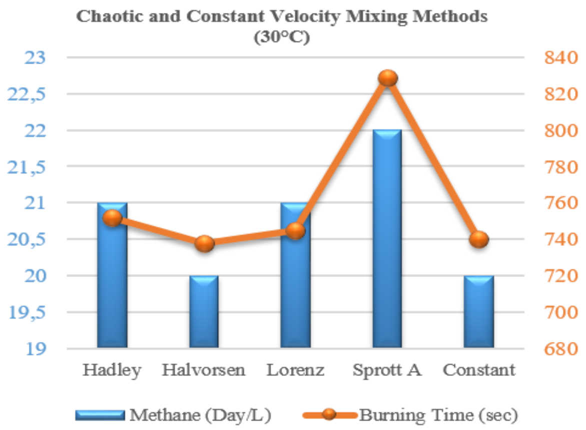

Figure 8. Comparison of methane gas production and combustion duration in 30^0C chaotic and constant speed mixing methods.

In both experiments, the Chaotic Sprott-A method achieved the highest biogas production efficiency and provided the longest combustion duration. This result indicates that chaotic mixing based on the Sprott-A equation is one of the most effective mechanisms for ensuring homogeneous substrate distribution and is a viable method for biogas production processes. Additionally, while temperature increases enhanced methane production across all methods, it was observed that chaotic methods optimized this increase more effectively.

In conclusion, different chaotic mixing methods extended the combustion duration of the produced biogas compared to fixed-speed mixing, with the Sprott-A method achieving an approximately 11% increase. Notably, the Chaotic Sprott-A method demonstrated the highest performance in terms of biogas production and yielded the best results in combustion duration, which determines the energy value of biogas. These findings highlight the effectiveness and potential of chaotic mixing methods in biogas production processes, presenting them as a significant alternative for industrial applications.

4. Conclusion

This study investigated the impact of chaotic mixing methods on biogas production efficiency and compared their effectiveness with conventional fixed-speed mixing. The experiments were conducted at 20°C and 30°C, and key performance indicators such as daily methane yield and combustion duration were analyzed to evaluate the efficiency of different mixing approaches. The findings demonstrated that chaotic mixing methods improved biogas production compared to fixed-speed mixing, with the Chaotic Sprott-A method achieving the highest methane production and the longest combustion duration under both temperature conditions. The results indicate that temperature acts as a catalytic factor in biogas production and that chaotic mixing techniques enhance efficiency. Furthermore, the findings suggest that the Chaotic Sprott-A mixing method is the most effective approach, providing both higher methane production and extended combustion duration, making it a promising technique for improving the performance of anaerobic digestion systems.

Future research should focus on the scalability of chaotic mixing techniques in larger biogas reactors, assess their applicability across different substrate types and reactor designs, and further validate their potential for real-world applications by investigating their effectiveness with various organic feedstocks.

Author Contributions

The percentages of authors' contributions are given below. All authors have reviewed and approved the article.

	M.S.S.	M.S.D.	M.Ç.K.
C	50	40	10
D	40	40	20
S	20	20	60
DCP	40	50	10
DAI	50	40	10
L	50	30	20
W	40	50	10
CR	40	40	20
SR	50	40	10
PM	15	15	70
FA	15	15	70

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declare that they have no conflict of interest in this study.

Ethical Approval Statement

Since this study did not involve any studies on animals or humans, ethics committee approval was not obtained.

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