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COMPARATIVE ANALYSIS OF MIXING REGIMES IN BIOGAS PLANTS FOR OPTIMIZATION OF THE STIRRING PROCESS

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Abstract. *Effective mixing in anaerobic bioreactors plays a crucial role in ensuring uniform temperature and substrate distribution, which directly affects the efficiency of organic matter degradation and biogas yield. This study investigates the influence of mixing intensity and regime on gas transfer, heat transfer, and substrate degradation during anaerobic digestion. Special attention was given to the experimental data obtained from the pilot solar-powered biogas plant. The results demonstrated that intermittent mixing (e.g., 5 minutes per hour) provided the same biogas yield as continuous mixing, but with substantially lower energy consumption. Continuous mixing did not result in a significant increase in methane yield compared to intermittent operation, while it was associated with markedly higher energy demand. In contrast, the absence of mixing impaired reactor performance—the volume of gas produced decreased, and temperature stratification was observed, indicating uneven heating of the medium and incomplete substrate degradation. In this work, international studies (2019–2024), including experimental investigations and CFD models, were analyzed to assess the effects of mixing regimes on decomposition kinetics, temperature uniformity, and methane yield, and to compare them with our results. For quantitative evaluation, energy balance equations (e.g., the Lindorfer model) and stoichiometric formulas were applied. The findings indicate that intermittent mixing is the optimal strategy, as it ensures a high degree of organic matter degradation and biogas yield while requiring significantly less energy than continuous mixing.*

Keywords: anaerobic digestion, mixing efficiency, gas and heat transfer, substrate degradation, biogas yield

1. Introduction

Anaerobic digestion (AD) is widely used worldwide for the treatment of organic waste and the production of biogas [1]. Kazakhstan is currently paying increasing attention to the development of renewable energy sources and carbon neutrality strategies. According to national energy policy, the share of renewable energy in electricity generation is expected to increase significantly by 2030. In this context, biogas technologies are considered a promising solution for the utilization of agricultural waste and renewable energy production [2]. By converting organic substrates into methane and carbon dioxide, AD reduces greenhouse gas emissions and generates a renewable form of fuel [1,3]. In particular, CFD-based kinetic models of gas–liquid mixture formation in anaerobic digesters typically integrate hydrodynamic simulation (Euler–Euler multiphase flow with k – ϵ turbulence closure) with biochemical reaction kinetics (ADM1-based substrate degradation and

methane production models), allowing prediction of mixing efficiency and methane yield under different operational regimes. The efficiency of AD systems is determined by both biochemical processes and physical exchanges within the reactor [4,5]. In particular, mixing strongly influences gas transfer and heat transfer: active agitation ensures uniform distribution of heat and substrate, whereas insufficient mixing leads to temperature stratification and stagnant zones [3,5]. Approximately 44% of large-scale biogas plants report sedimentation problems due to improper mixing [4]. A significant proportion of livestock in Kazakhstan is concentrated in small-scale farms with relatively low numbers of cattle. Therefore, compact and energy-efficient biogas plants with simple mixing systems are particularly important for decentralized agricultural applications [6].

The analysis of energy costs for maintaining the optimal mixing mode of organic waste in the installation allows us to conclude that the mixing method is most acceptable by means of multilevel reciprocating movement of biomass. Most authors believe [7] that the mixed biomass in the reactor should have a limited velocity (up to 0,5 m/s), since a high velocity of the substrate is unprofitable from a microbiological point of view. In addition, although it leads to an increase in the intensity of heat transfer, it also increases the energy consumption for mixing. It is easy to verify this by analyzing the known equations of heat transfer and hydraulic resistances during turbulent fluid movement in a tube heat transfer [7].

$$Nu = 0,021Re^{0.8} \times P_z^{0.43} \quad (1)$$

$$\Delta P = \frac{\xi_{mp} \ell}{d} + \frac{\sum \xi_m \rho \omega^2}{2}, \quad (2)$$

where Nu is the Nusselt number, Re is the Reynold's number, P_z is the Prandtl number, ΔP is the hydraulic resistance of the heat exchanger on the side of the given working medium, ω is the speed of the working environment, ρ is the density of the medium, ℓ is the channel length, d is the channel diameter, ξ is the coefficient of friction and $\sum \xi_m$ is the sum of the local resistance coefficient. From (1) and (2) are

$$\alpha = A1 \omega^{0.8}, \quad (3)$$

$$\Delta \rho = A2 \omega^{1.75}, \quad (4)$$

where $A1$ and $A2$ are the coefficients of proportionality.

From the obtained ratios, it can be seen that a doubling of the flow velocity provides a 1.75-fold increase in heat transfer, and in this case, the increase in hydraulic resistance occurs up to 3.4 times.

From the above considerations, it follows that the intensification of the process cannot be considered in isolation from the energy costs involved. Mixing also affects substrate degradation, i.e., the efficiency of organic solids breakdown. Sufficient mixing intensity enhances contact between fresh substrate and active sludge (inoculum), thereby improving mass transfer of enzymes and nutrients, which accelerates hydrolysis and subsequent degradation stages. In recent years, a considerable number of studies have been devoted to optimizing mixing strategies in anaerobic digestion in order to improve its efficiency. Within the framework of this study, a review was carried out covering scientific publications from 2019 to 2024, including both experimental investigations and computational fluid dynamics (CFD) modeling of hydrodynamics in anaerobic reactors. The CFD approaches considered in the reviewed studies are mainly based on multiphase Euler–Euler flow modeling combined with the k – ϵ turbulence model, often coupled with biochemical kinetic sub-models such as ADM1 and first-order hydrolysis kinetics to describe gas–liquid mixing, mass transfer, and methane formation processes. Li et al. (2022) emphasized that mixing “significantly influences methane production in AD” and concluded that periodic mixing is preferable for maximizing biogas yield [8].

Singh et al. (2022) noted that mixing improves substrate–microbe contact and enhances thermal homogeneity, thereby reducing volatile fatty acid (VFA) concentrations and increasing organic removal efficiency [4]. Conversely, mechanical agitation may cause microbial floc disruption and suppression of syntrophic bacteria, as observed in several experiments [4]. Indeed, excessively high mixing intensity can increase the availability of soluble substrates but may also disrupt biomass structure, sometimes resulting in a reduction of overall methane yield [4]. Most studies indicate that intermittent mixing often provides the best

balance. For instance, Kowalczyk et al. (2013) demonstrated that reducing daily mixing time from 7 hours to 2 hours resulted in 12–29% energy savings without compromising methane yield [9].

For example, Bose et al. (2021) added granular activated carbon into a CSTR and reported that the methane yield in the non-mixed case reached 318 mL CH₄/g COD (chemical oxygen demand), compared to ~290 mL/g in mixed conditions [10]. This suggests that specific factors such as substrate type, additives, and reactor design can modify the impact of mixing on microbial performance.

The literature also highlights the physical consequences of mixing. Mixing enhances mass transfer by reducing boundary layers around biomass and redistributing the substrate [5]. Hu et al. (2021) visualized mixing using LIF and PIV techniques and showed that poor mixing leads to substrate accumulation zones and dead zones in reactors with high solid content [11]. Mixing also contributes to temperature homogenization: in unmixed reactors, thermal stratification due to buoyancy often occurs [3], potentially creating “cold zones” that slow hydrolysis. El Ibrahim et al. (2021) measured unmixed reactors and found significant vertical temperature gradients. Their CFD simulations indicated that double-wall heating could eliminate this effect, linking thermal homogeneity directly to methane yield [3]. These findings underline that the role of mixing in heat transfer is as crucial as in mass transfer [3,5]. Experimental data and mathematical modeling are used for quantitative assessment. For example, Lindorfer (2007) developed a dynamic model of the energy balance of a bioreactor, in which the net power output is expressed by the equation [12]:

$$\frac{dP_{net}}{dt} = P_{prod,e} - (P_{loss,pump} + P_{loss,stir} + P_{loss,rad} + P_{loss,sub}) + P_{loss,term} + P_{loss,mic} \quad (5)$$

where $P_{prod,e} = Q_G \cdot P_{CH_4} \cdot HC \cdot \eta_e$ and $P_{prod,therm} = Q_G \cdot P_{CH_4} \cdot HC \cdot \eta_t$ – electric and thermal power outputs of biogas, $P_{loss,terms}$ and others – the cost of pumping, mixing, heating the substrate, radiation, etc.

Using such formulas, it is possible to estimate the yield of clean energy under various mixing modes. For substrate decomposition, classical stoichiometry (Buswell's equation) predicts the yields of CH₄/CO₂ from the composition of C:H:O:N [13], and kinetic models (for example, first-order or ADM1) describe the rate constants. In practice, mixing affects both the effective rate of decomposition (preventing deposition of the substrate) [4,5] and the proportion of the substrate converted to gas (by reducing pH or inhibiting PLA [4]). Thus, world practice shows that the mixing mode has a profound effect on the productivity of the AD. Continuous mixing ensures uniformity, but requires a lot of energy [4,12]. Intermittent mixing has become the optimal option [4,8]. The absence of mixing minimizes energy consumption, but creates a risk of stratification and reduced conversion [3,4].

This study investigates the effect of three mixing regimes (continuous, intermittent, and no mixing) on the performance of AD. Using experimental data from a biogas plant, we evaluate how each regime influences heat and mass transfer, substrate degradation rate, and methane yield. These results are compared with an extensive literature review covering international studies from 2019–2024, including experimental research [5,8]. Quantitative models are also applied, such as the energy balance equation, to interpret the obtained results [12]. The main objective is to determine the optimal mixing regime in anaerobic bioreactors that ensures maximum methane productivity while minimizing energy consumption for mixing and maintaining thermal stability.

2. Materials and methods

2.1. Materials

The object of the study was the operating regimes of anaerobic digestion (no mixing, intermittent mixing, and continuous mixing) evaluated in a solar-assisted biogas reactor under mesophilic conditions.

The experimental system consisted of a solar-assisted vertical biogas reactor designed for anaerobic digestion of cattle manure. The reactor had a cylindrical body with a conical bottom and was equipped with a water jacket connected to a solar thermal collector to maintain stable operating temperatures. A two-blade mechanical stirrer was installed inside the reactor to provide controlled mixing of the substrate. The digester was mounted on a supporting frame to ensure structural stability during operation [14,15]. The main research object was the determination of the optimal mixing regime that maximizes methane production while minimizing energy consumption in a solar-assisted biogas reactor.

The substrate used in the experiments was a mixture of cattle manure and water with an initial carbon-to-nitrogen ratio (C/N) of approximately 25 and a total solids (TS) content of about 8%. The reactor was operated under mesophilic conditions at a target temperature of 37 ± 1 °C.

The operational parameters were maintained as follows:

- Organic Loading Rate (OLR): $2 \text{ kg VS m}^{-3} \text{ d}^{-1}$;
- Hydraulic Retention Time (HRT): 20 days;
- Daily substrate feeding;
- Reactor operation under stable mesophilic conditions.

Three mixing regimes were investigated:

1. No mixing (NM): the stirrer remained switched off during the entire digestion process.
2. Intermittent mixing (IM): the stirrer operated for 5 min every hour (5 min h^{-1}).
3. Continuous mixing (CM): the stirrer operated continuously at 60 rpm throughout the day.

The comparison of these operating modes enabled the evaluation of their influence on heat transfer, gas transfer, substrate degradation, methane production, and overall energy efficiency.

Figure 1 shows the external appearance of the digester, equipped with a solar heating system using support frame. The configuration of this biogas plant includes a water jacket and a two-blade mechanical stirrer.



Fig.1. Experimental solar-assisted vertical biogas plant/

2.2 Research methods

The reactor performance was monitored using calibrated measuring instruments to ensure reliable and repeatable experimental results.

The following parameters were measured during the experiments:

- Temperature: digital immersion thermometers with an accuracy of $\pm 0.5 \text{ }^\circ\text{C}$ installed at the middle section of the reactor. Measurements were recorded every 2 h.
- pH: determined using colorimetric indicator strips and periodically verified by a portable electrochemical pH meter equipped with automatic temperature compensation. Measurements were performed every 4 h.
- Biogas composition (CH_4 and CO_2): measured using a portable nondispersive infrared (NDIR) gas analyzer with a measurement range of 0–100% and an accuracy of $\pm 1\%$.
- Pressure: measured using a diaphragm pressure gauge (0–200 kPa, accuracy $\pm 0.25\%$).
- Biogas volume: continuously recorded using a wet-type diaphragm gas meter with an accuracy of $\pm 1\%$.
- Substrate level: monitored by an ultrasonic distance sensor mounted at the top of the reactor.

Digestate samples were periodically collected from the upper, middle, and lower sections of the reactor for laboratory analysis.

The determination of volatile solids (VS), chemical oxygen demand (COD), and volatile fatty acids (VFA) was carried out according to internationally recognized analytical procedures. COD analysis was performed following APHA Standard Methods for the Examination of Water and Wastewater. The determination of bio-based carbon content was conducted in accordance with EN 16640:2017 “Bio-based products – Bio-based carbon content – Determination of the bio-based carbon content using the radiocarbon

method". Methane concentration was determined by gas chromatography. The obtained experimental data were used to evaluate substrate degradation, methane productivity, and reactor energy efficiency.

2.3. Analytical Calculations

The chemical oxygen demand (COD) was calculated as:

$$COD = \frac{(A-B) \cdot N \cdot 8000}{V}, \text{ mg/L} \quad (6)$$

where A is the volume of titrant in the blank experiment (ml), B is the volume in the sample (ml), N is normality, and V is the volume of the sample (ml).

The concentration of volatile fatty acids (VFA) was calculated using:

$$VFA = \frac{V_{NaOH} \cdot N \cdot 60 \cdot 1000}{V_{sample}}, \text{ mg/L} \quad (7)$$

where V_{NaOH} is the volume of NaOH (ml), N is normality, 60 is m.m. CH_3COOH , V_{sample} is the volume of the sample (ml).

The removal coefficient (%) was calculated from incoming and outgoing solid particles:

$$VS_{removal} = \frac{VS_{in} - VS_{out}}{VS_{in}} \times 100\% \quad (8)$$

where VS_{in} is VS in the input substratum, VS_{out} is in the digest.

The methane yield was expressed in terms of g of consumed methane and m^3 of reactor volume.

$$Y_{CH_4 VS} = \frac{V_{CH_4}}{m_{VS_{destroyed}}} \quad (9)$$

where V_{CH_4} is the volume of methane, $m_{VS_{destroyed}}$ is the mass of destroyed VS, g.

$$Y_{CH_4 vol} = \frac{V_{CH_4}}{V_{reactor}} \quad (10)$$

where V_{CH_4} is the volume of methane, $V_{reactor}$ is the volume of the reactor (m^3).

2.4. Energy Balance Analysis

The Lindorfer model was used: electric energy P_{elect}^{prod} and thermal energy P_{therm}^{prod} from biogas were calculated using the formula [11]:

$$P_{elect}^{prod} = Q_G \cdot P_{CH_4} \cdot H_C \eta_{elect} \quad (\text{kWhd}^{-1}) \quad (11)$$

$$P_{therm}^{prod} = Q_G \cdot P_{CH_4} \cdot H_C \eta_{therm} \quad (\text{kWhd}^{-1}) \quad (12)$$

where Q_G is the biogas production (m^3d^{-1}), P_{CH_4} is the methane content (%), H_C is the calorific value of methane (kWh Nm^{-3}), η_{elect} is the electrical degree of efficiency (-) and η_{therm} is the thermal degree of efficiency (-) [11].

Stirrer losses according to the equation:

$$P_{stir}^{loss} = V_{liq} \cdot S \quad (\text{kWhd}^{-1}) \quad (13)$$

where V_{liq} is the liquid volume (m^3), S is the specific power of the stirrer (kWm^{-3}) and t_s is the time for stirring (hd^{-1}).

Pump losses according to the equation:

$$P_{pump}^{loss} = Q_{in} \cdot H \rho g t_p \frac{1}{\eta_{ecc_warm}} (kWhd^{-1}) \quad (14)$$

where Q_{in} is the inflow rate ($kg s^{-1}$), H is the conveyor height (m), ρ is the density of the pumped media ($kg m^{-3}$), g is the acceleration of gravity (ms^{-2}), t_p is the time for pumping (hd^{-1}) and η_{ecc_warm} is the degree of efficiency (-)

Radiation losses according to the equation:

$$P_{rad}^{loss} = K_{heat_trans} [(T_{liq} - T_{ambient}) V_{liq} + (T_{gas} - T_{ambient}) \times (V_{tot} - V_{liq})] \cdot \frac{2}{r} \cdot \frac{24}{1000} (kWhd^{-1}) \quad (15)$$

where K_{heat_trans} is the heat transfer coefficient ($Whm^{-2}h^{-1} K^{-1}$), T_{liq} is the temperature of the substrate within the digester (K), $T_{ambient}$ is the ambient temperature, V_{liq} is the liquid volume (m^3), T_{gas} is the gas temperature (K), V_{tot} is the total digester volume (m^3) and r is the radius of the digester (m).

Heat transfer losses according to the equation:

$$P_{sub_heat}^{loss} = Q_{in} c (T_{digester} - T_{substrate}) \frac{1}{3,6} (kWhd^{-1}) \quad (16)$$

where Q_{in} is the reactor inflow ($m^3 d^{-1}$), c is the heat capacity of the substrate ($kJ kg^{-1} K^{-1}$), $T_{digester}$ is the temperature of the digester (K) and $T_{substrate}$ is the temperature of the stored substrate (K).

The calculated energy indicators were used to compare the effectiveness of the investigated mixing regimes and to determine the optimal operating mode for methane production and energy utilization. In addition to experimental analysis, CFD-informed kinetic interpretation was used, where multiphase flow behavior and substrate conversion were analyzed using Euler–Euler hydrodynamic assumptions coupled with ADM1-based biochemical kinetics.

3. Results and discussion

The experiments revealed clear trends in the production of biogas and methane in three modes. Table 1 contains average data on biogas production, methane content, VS removal, and mixing costs for each regime.

Table 1. AD productivity in an experimental biogas plant under various mixing modes (OLR = 2 $kg/m^3 \cdot day$, 37°C, HRT = 20 days).

Mixing model	Biogas production ($l m^3 \cdot day$)	CH ₄ (%)	Removing VS (%)	Mixing energy (kWh/day)
Without stirrer	0.65	58	48	0.00
Intermittent (5 min/h)	0.78	61	53	1.5
Continuous (60 rpm)	0.75	60	56	4.8

Figure 2 presents the effect of different mixing regimes on anaerobic digestion performance. Figure 2(a) illustrates methane yield and VS removal efficiency under no-mixing, intermittent, and continuous mixing conditions, while Figure 2(b) shows the corresponding temperature gradients within the reactor. The results indicate that intermittent mixing achieved the highest methane concentration (61% CH₄), slightly exceeding that of continuous mixing (60%). Continuous stirring provided the greatest VS removal efficiency, approximately 5% higher than that observed in the non-mixed reactor. However, continuous mixing required about three times more energy (4.8 versus 1.5 kWh per day) than intermittent mixing. In contrast, the reactor without stirring consumed no mechanical energy, but its methane production was about 15% lower than in the intermittent stirring mode, which is consistent with reports that the absence of stirring reduces the overall gas output [4]. It is noteworthy that the pH and VFA values indicate a slight accumulation of VFA in the static reactor, while the content of acetate and propionate remains at the lowest level during periodic stirring. These trends are consistent with previous findings that periodic stirring stabilizes the chemical composition of the reactor more effectively than without stirring [4].

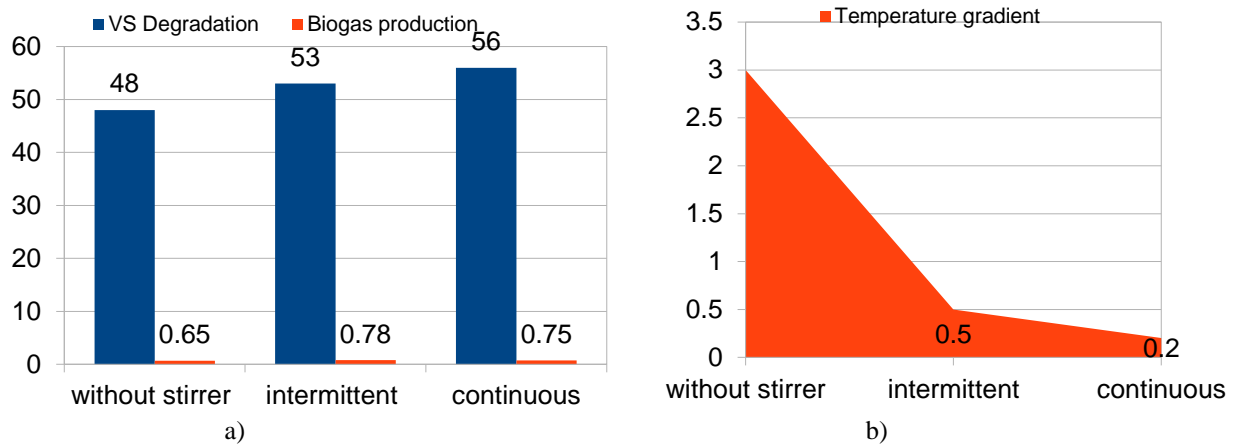


Fig.2. Effect of mixing regimes on anaerobic digestion performance: (a) methane yield and VS removal efficiency; (b) temperature gradient inside the reactor.

The results demonstrate a trade-off between mixing regimes. Continuous mixing ensured the most uniform substrate distribution and enhanced degradation (see Table 2), as predicted by mixing models [12]. It prevented solid settling and increased organic matter conversion; however, the associated energy demand was very high [4,12]. Intermittent mixing achieved nearly the same level of VS removal with considerably lower energy consumption. This is consistent with the literature: Singh et al. and others reported that short mixing pulses provide almost the same gas yield as continuous mixing, while using electricity more efficiently [4]. In our experiments, a 5 min/h pulse proved effective, although the optimal intervals may vary for other scales and substrates. From a mechanistic perspective, intermittent mixing combines several advantages: short bursts distribute fresh substrate, while pauses allow microbes to operate without strong shear stress. This typically promotes acetolactic methanogens and prevents the accumulation of volatile fatty acids (VFAs) [4]. In our reactor, VFA concentrations stabilized at lower levels under the intermittent regime. As noted by Caillet et al., improved mixing enhances the mass transfer coefficient and eliminates thermal gradients [5].

The energy balance highlights the advantages of the intermittent regime: according to the Lindorfer model [12], continuous mixing requires ~ 0.14 kWh/m³·d solely for the agitator, whereas intermittent mixing needs only ~ 0.04 . At the same time, the thermal and electrical energy recovered from biogas (≈ 6.5 kWh/m³·d) shows a smaller reduction under intermittent operation. The resulting net power (~ 6.3 kWh/m³·d) was higher than under continuous mixing (~ 6.1). This is consistent with the findings of El Ibrahim et al. (2025), who reported that combining mixing with heating can reduce energy consumption by more than 75% [16]. Our results also support the observations of Kowalczyk et al., who reported a 29% reduction in energy demand when mixing time was shortened, as well as the conclusion of Semen et al. that longer pauses lead to higher yields.

It should be noted that the specific methane yield (per g VS) was the lowest in the non-stirred reactor, which is consistent with the reports of Bose et al. on efficiency losses in the absence of mechanical agitation [4]. Nevertheless, some self-induced convective flows still occurred without a stirrer. Our measurements revealed a vertical temperature gradient of ~ 3 °C, confirming the CFD modeling of El Ibrahim, which showed stratification in the absence of mixing [3]. This likely slowed down hydrolysis in the cooler upper zone, further highlighting the benefits of short mixing periods in ensuring uniform heating and mixing.

An additional comparative analysis was conducted between the experimental results and the predictions of mathematical models based on differential equations (Table 3, Fig. 3), as reported in the studies of Li et al. [8], Singh et al. [4], El Ibrahim et al. [3], Lindorfer [12], and other researchers.

Table 3. Data from mathematical models based on differential equations

Mixing model	CH ₄ (%)	Removing VS (%)	Temperature gradient (°C)	Clean energy (kWh/m ³ day)
Without stirrer	57	47	3,2	5,4
Intermittent(5 min/h)	62	52	0,4	6,35
Continuous (60 rpm)	60	55	0,1	6,05

Figure 3 presents a comparison between the obtained experimental data and the model predictions. Figure 3(a) shows the methane concentration (CH_4 , %), Figure 3(b) presents the volatile solids removal efficiency (VS removal, %), Figure 3(c) illustrates the temperature gradient within the reactor ($^{\circ}\text{C}$), and Figure 3(d) depicts the net energy production ($\text{kWh m}^{-3} \text{ day}^{-1}$).

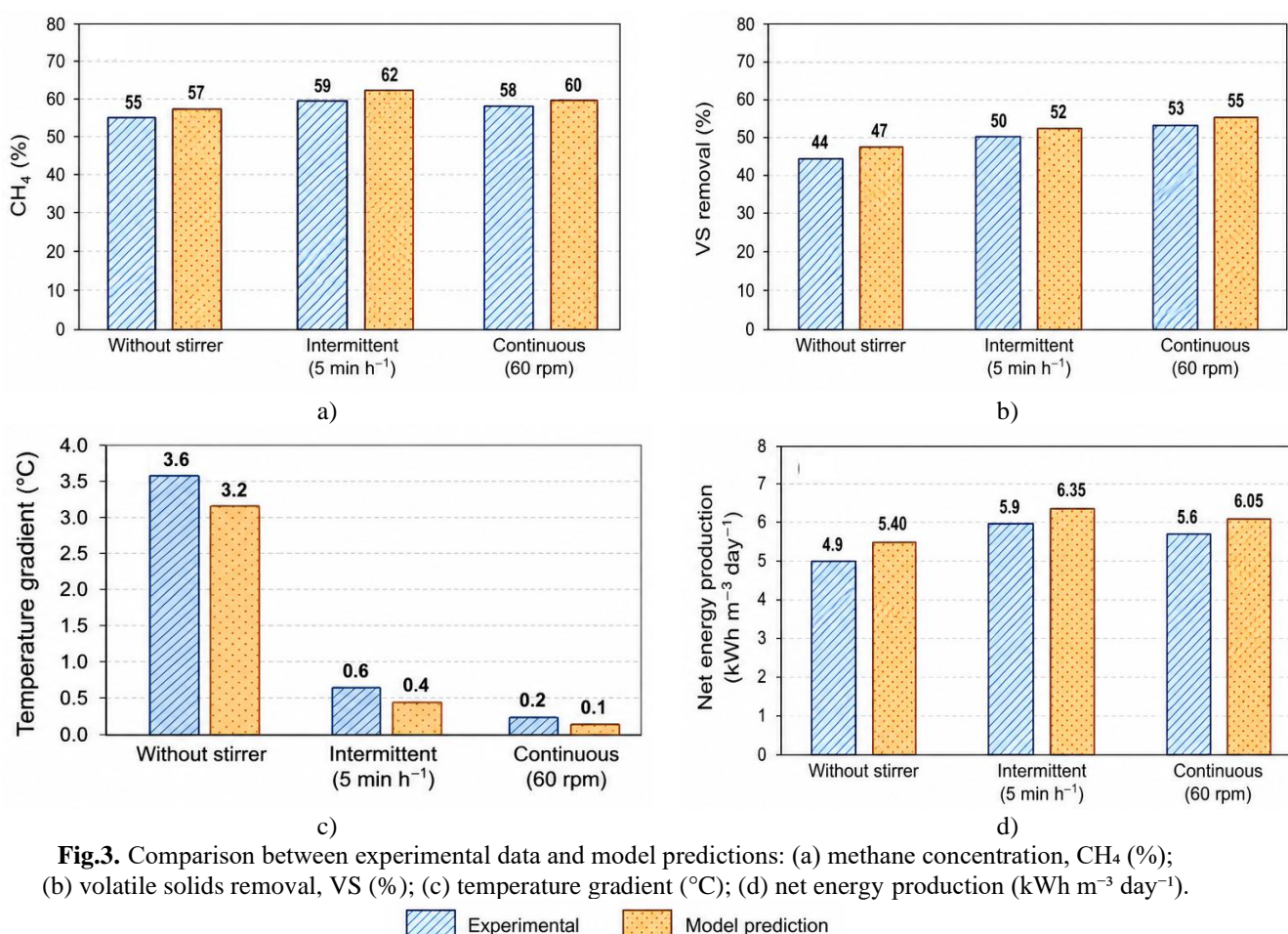


Fig.3. Comparison between experimental data and model predictions: (a) methane concentration, CH_4 (%); (b) volatile solids removal, VS (%); (c) temperature gradient ($^{\circ}\text{C}$); (d) net energy production ($\text{kWh m}^{-3} \text{ day}^{-1}$).

Experimental Model prediction

The following computational models were used:

- a first-order kinetic model for hydrolysis;
- the structured ADM1 model describing the dynamics of VFAs, pH, and methanogenesis;
- the Lindorfer energy model accounting for power balance.

Thus, both experimental data and literature sources converge on the conclusion that an intermediate regime between the extremes is optimal [4,12]. Continuous mixing does not provide a significant gain in yield compared to intermittent operation but consumes considerable energy. The complete absence of mixing saves energy but reduces biogas yield and causes stratification. Intermittent mixing enables nearly maximal yield at substantially lower costs [4]. Our data show that short mixing pulses are sufficient to sustain microbial activity and prevent inhibition (with VFAs remaining at low levels). In line with global studies, we recommend periodic mixing (e.g., 5–15 min every 1–4 h) at moderate speed to break the surface crust and keep particles in suspension without creating excessive shear stress [4,8].

4. Conclusion

The study clearly demonstrates that the mixing regime has a profound impact on the efficiency of anaerobic digestion. Based on experiments and an extensive literature review, we conclude that intermittent mixing is the optimal strategy, as it maintains high methane yield and degradation efficiency at substantially lower energy costs than continuous mixing. In particular, short mixing pulses (5–10 min every 1–2 h) resulted in nearly the same biogas yield as continuous mixing but required three times less electricity, consistent with

the findings of other authors. Continuous mixing did not improve yield compared to intermittent operation but significantly increased energy demand. The non-mixed regime provided the lowest yield and showed temperature stratification, although it required minimal energy input.

Therefore, the analysis of energy expenditures in anaerobic digestion systems indicates that efforts to reduce the overall energy intensity should primarily focus on heat recovery from digested organic residues and on the optimization of biomass mixing within bioreactors. Considering the intensive treatment of biomass under thermophilic conditions, the application of high-efficiency heat exchangers appears most appropriate. Furthermore, the selected equipment must comply with the operational requirements of systems handling non-Newtonian fluids, a characteristic property of biomass.

In practice, it is recommended to design AD plants with programmable intermittent mixing. For instance, mixer operation can be synchronized with heating periods. The reactor geometry (height-to-diameter ratio) should promote natural circulation during idle phases. Operators should monitor biogas yield and temperature profiles to detect potential stratification. These recommendations are consistent with global trends in optimizing the energy efficiency of AD systems.

In the future, it will be reasonable to refine CFD-kinetic models for specific operating conditions and substrates. Overall, the experimental results combined with the analysis of international studies demonstrate that intermittent mixing is the optimal regime for anaerobic bioreactors. It ensures effective heat and mass transfer, a high degree of substrate degradation, and maximum biogas yield at minimal energy input.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Yessenzhol D.K.: investigation, visualization, writing—original draft; **Sakipov K.Ye.:** supervision, Writing – review & editing; **Imomov Sh.J.:** project administration, conceptualization; **Sharipov M.Z.:** methodology, formal analysis, **Majitov J.A.:** data curation, validation; **Akhmetov S.K.:** data curation. The final manuscript was read and approved by all authors.

Statement on the use of Artificial Intelligence

During the preparation of this manuscript, artificial intelligence tools were used solely for language editing and grammatical improvement. No AI tools were used to generate scientific content, analysis, results, or conclusions.

Data Availability Statement

The data are available upon reasonable request from the authors.

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