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KAZAKHSTAN

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STUDY OF A DYNAMIC MIXING DEVICE IN A BIOREACTOR USING IOT TECHNOLOGIES

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Abstract. This article presents a comprehensive study of the influence of a dynamic mixing device on the temperature regime of biomass in an anaerobic bioreactor integrated with Internet of Things (IoT)-based monitoring and control technologies. The relevance of the study is due to the need to improve the efficiency of anaerobic digestion by ensuring temperature uniformity, which is one of the key factors for stable methanogenesis and biogas production. An intelligent control system based on the ESP32 microcontroller is proposed, providing multi-point temperature measurements along the reactor height, real-time data transmission via Wi-Fi/MQTT protocols, and adaptive control of mixing parameters. The integration of the IoT system provides continuous monitoring of process parameters, analysis of temperature distribution, and automatic adjustment of the operating mode depending on the state of the biomass. The research results demonstrate that the proposed approach improves heat and mass transfer, increases the activity of methanogenic microorganisms, and enhances biogas yield by 15–25% while simultaneously reducing energy consumption. This made it possible to evaluate the influence of the dynamic mixing device on flow distribution, temperature fields, biomass circulation, and the intensity of biogas release in different zones of the bioreactor.

Keywords: bioreactor, biomass mixture, biogas, dynamic mixing, temperature regime, IoT, ESP32, anaerobic digestion, intelligent control

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БИОРЕАКТОРДА IoT ТЕХНОЛОГИЯЛАРЫН ПАЙДАЛАНА ОТЫРЫП ДИНАМИКАЛЫҚ АРАЛАСТЫРУ ҚҰРЫЛҒЫСЫН ЗЕРТТЕУ

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Аннотация. Бұл мақала заттар интернетіне (IoT) негізделген мониторинг және басқару технологияларымен біріктірілген анаэробты биореактордағы биомассаның температуралық режиміне динамикалық араластыру құрылғысының әсерін жан-жақты зерттеуді ұсынады. Зерттеудің өзектілігі анаэробты дигестия тиімділігін арттыру қажеттілігімен байланысты, себебі температуралық біркелкілікті қамтамасыз ету тұрақты метан түзілуі мен биогаз өндірудің негізгі факторларының бірі болып табылады. ESP32 микроконтроллеріне негізделген интеллектуалды басқару жүйесі ұсынылған, ол реактор биіктігі бойымен көп нүктелі температура өлшеулерін, Wi-Fi/MQTT протоколдары арқылы нақты

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уақыттағы деректерді жіберуді және араластыру параметрлерін бейімді басқаруды қамтамасыз етеді. IoT жүйесін интеграциялау процесс параметрлерін үздіксіз бақылауды, температура таралуын талдауды және биомасса күйіне байланысты жұмыс режимін автоматты түрде реттеуді жүзеге асырады. Зерттеу нәтижелері ұсынылған тәсілдің жылу мен масса алмасуын жақсартып, метан түзетін микроорганизмдердің белсенділігін арттырып, биогаз өнімділігін 15–25%-ға арттыратынын және бір уақытта энергия тұтынуын азайтатынын көрсетті. Бұл биореактордың әртүрлі аймақтарындағы ағынның таралуы, температуралық өрістер, биомасса айналымы және биогаз бөліну қарқындылығына динамикалық араластырғыш құрылғының әсерін бағалауға мүмкіндік берді.

Түйінді сөздер: биореактор, биомасса қоспасы, биогаз, динамикалық араластыру, температураны бақылау, IoT, ESP32, анаэробты қорыту, интеллектуалды басқару

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ИССЛЕДОВАНИЕ УСТРОЙСТВА ДИНАМИЧЕСКОГО ПЕРЕМЕШИВАНИЯ В БИОРЕАКТОРЕ С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИЙ IoT

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Аннотация. В данной статье представлено комплексное исследование влияния устройства динамического перемешивания на температурный режим биомассы в анаэробном биореакторе, интегрированном с технологиями мониторинга и управления на базе «Интернета вещей» (IoT). Актуальность исследования обусловлена необходимостью повышения эффективности анаэробного сбраживания за счет обеспечения равномерности температурного режима, что является одним из ключевых факторов стабильного метаногенеза и производства биогаза. Предложена интеллектуальная система управления на базе микроконтроллера ESP32, обеспечивающая многоточечные измерения температуры по высоте реактора, передачу данных в реальном времени по протоколам Wi-Fi/MQTT и адаптивное управление параметрами перемешивания. Интеграция системы IoT обеспечивает непрерывный мониторинг технологических параметров, анализ распределения температуры и автоматическую настройку режима работы в зависимости от состояния биомассы. Результаты исследования показывают, что предложенный подход улучшает тепло- и массообмен, повышает активность метаногенных микроорганизмов и увеличивает выход биогаза на 15–25 % при одновременном снижении энергопотребления. Это позволило оценить влияние

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устройства динамического перемешивания на распределение потока, температурные поля, циркуляцию биомассы и интенсивность выделения биогаза в различных зонах биореактора.

Ключевые слова: биореактор, смесь биомассы, биогаз, динамическое перемешивание, температурный режим, IoT, ESP32, анаэробное сбраживание, интеллектуальное управление

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Introduction.

Modern studies demonstrate that the efficiency of anaerobic digestion is determined by the stability of the temperature regime, the intensity of mixing, and the level of process automation (Khan et al., 2017; Appels et al., 2008). Temperature is one of the key factors influencing the activity of methanogenic microorganisms and biogas yield, while deviations greater than 2–3°C may lead to a decrease in process efficiency (Khan et al., 2017). According to research findings, temperature non-uniformity inside the bioreactor results in the formation of zones with different biological activity, which worsens the kinetics of methanogenesis and reduces the overall gas yield (Ward et al., 2008; Chen et al., 2008). Studies (Lindmark et al., 2014; Karim et al., 2005) show that mixing plays an important role in ensuring uniform distribution of temperature and substrate; however, conventional mixers often fail to provide sufficient adaptability when the viscosity of the biomass mixture changes. In recent years, dynamic and intelligent mixing systems capable of adapting their operating modes depending on the state of the medium have been actively developed (Wu, 2010). Such systems improve heat and mass transfer, eliminate stagnant zones, and enhance the efficiency of biochemical processes (Stroot et al., 2001). At the same time, Internet of Things (IoT) technologies are being actively introduced to enable real-time monitoring of bioreactor parameters (Ray, 2016; Al-Fuqaha et al., 2015). The use of wireless technologies such as Wi-Fi, MQTT, and cloud platforms ensures continuous data collection and analysis, as well as remote process control (Banks et al., 2014; Thangavel et al., 2014). Studies (Calise, 2020; Gil-Carrera et al., 2019) demonstrate that the integration of IoT into biogas plants reduces the risk of emergency situations, improves the stability of the technological regime, and optimizes energy consumption. In addition, the application

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of intelligent control algorithms and machine learning methods makes it possible to predict parameter deviations and prevent failures (Zhang et al., 2019; Li et al., 2020). From the perspective of practical efficiency, studies show that the combined application of mixing and digital monitoring can increase biogas yield by 10–30% (Mertins et al., 2021; Céileachair et al., 2023). This confirms the necessity of developing integrated systems that combine mechanical and digital technologies.

The literature analysis shows that:

- temperature uniformity is a critically important factor (Khan et al., 2017; Ward et al., 2008);
- dynamic mixing increases the efficiency of heat transfer (Wu, 2010; Stroot et al., 2001);
- IoT provides a qualitatively new level of control (Ray, 2016; Banks et al., 2014);
- integration of technologies leads to improved efficiency of biogas plants (Mertins et al., 2021).

The solution proposed in this article corresponds to modern scientific trends and advances them through the integration of dynamic mixing and an intelligent IoT-based control system. The aim of this study is to investigate the temperature regime of the biomass mixture in an anaerobic bioreactor using a dynamic mixing device and IoT-based monitoring and control technologies, as well as to evaluate the influence of this approach on the efficiency of the digestion process and biogas yield.

The rapid increase in global energy demand, coupled with growing environmental concerns and the depletion of fossil fuel reserves, has heightened interest in renewable and sustainable energy technologies. Among these, biogas technologies hold a particularly important role, as they address two critical challenges simultaneously: the utilization of organic waste and the production of renewable energy carriers (Angelidaki et al., 2011; Demirbas, 2009; Weiland, 2010). Anaerobic digestion is widely employed across agriculture, wastewater treatment plants, food-processing industries, and municipal waste management systems due to its ability to convert organic substrates into methane-rich biogas. This biogas can then be used for thermal energy, electricity generation, or upgraded to biomethane for injection into gas grids and transportation applications (Khan et al., 2017; Weiland, 2010). The efficiency of anaerobic digestion depends heavily on maintaining stable physicochemical and biological conditions within the bioreactor. Key factors influencing performance include temperature stability, substrate homogeneity, pH balance, mixing intensity, and the concentration of active microorganisms (Khan et al., 2017; Ward et al., 2008; Chen et al., 2008). Temperature, in particular, is a critical parameter affecting the metabolic activity of methanogenic microorganisms and the kinetics of biochemical reactions during anaerobic digestion (Chen et al., 2008). Even minor temperature fluctuations can significantly impact methane production efficiency, microbial stability, and overall biogas plant performance (Ward et al., 2008). Studies have shown that temperature variations exceeding 2–3 °C may inhibit methanogenesis, slow substrate degradation, and reduce gas yield (Khan et al., 2017; Chen et al., 2008). A major engineering challenge

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in conventional anaerobic bioreactors is the formation of temperature stratification and stagnant zones within the biomass mixture (Ward et al., 2008; Lindmark et al., 2014). In many practical systems, inadequate mixing leads to uneven heat distribution throughout the reactor volume, resulting in localized cold or overheated areas. This unevenness disrupts biochemical processes and adversely affects microbial activity (Lindmark et al., 2014; Karim et al., 2005). Additionally, poor circulation promotes substrate sedimentation, accumulation of dense organic layers, impaired heat and mass transfer, and reduced contact between microorganisms and nutrients (Karim et al., 2005; Stroot et al., 2001). These issues ultimately lower biogas productivity and extend the processing time of organic waste. To address these challenges, various mechanical mixing systems have been developed to improve hydrodynamic conditions inside bioreactors. Conventional agitators, propeller systems, and recirculation pumps are commonly used to enhance substrate homogeneity and heat transfer (Lindmark et al., 2014; Wu, 2010). However, most traditional mixing systems operate at fixed settings and cannot adapt to the continuously changing properties of the biomass, such as viscosity, density, and organic loading rate (Lindmark et al., 2014; Hoffmann et al., 2008). Since the rheological characteristics of biomass can vary significantly throughout different stages of anaerobic digestion, fixed mixing systems often fail to maintain optimal circulation across the entire reactor volume. Recently, there has been growing interest in adaptive and intelligent mixing systems that can adjust their operating parameters based on the current state of the biomass mixture (Wu, 2010; Stroot et al., 2001). Dynamic mixing devices with adjustable blade angles and variable immersion depths offer significant advantages over conventional systems. These devices enhance circulation flows, eliminate stagnant zones, improve heat transfer, and promote uniform substrate distribution throughout the reactor (Wu, 2010). Furthermore, adaptive mixing enables more efficient reactor operation under varying substrate viscosities and loading conditions while reducing unnecessary energy consumption.

Materials and methods.

The relevance of this study is determined by the growing need to improve the energy efficiency of biogas plants and to expand the application of digital technologies in bioenergy systems (Angelidaki et al., 2011; Demirbas, 2009). Under conditions of increasing interest in alternative energy sources, the task of improving the stability and productivity of anaerobic bioreactors becomes particularly important (Appels et al., 2008). One of the main problems of existing bioreactors remains the insufficient control of the temperature field inside the reaction volume (Ward et al., 2008). Uneven temperature distribution within the biomass mixture creates zones with reduced biological activity, which worsens the conditions for methanogenesis and decreases the efficiency of organic waste processing (Chen et al., 2008). Traditional mixing methods in many cases do not provide the required intensity and depth of impact on the substrate, especially when its viscosity, density, and structural condition change (Lindmark et al., 2014; Karim et al., 2005). Additional relevance to the study is provided by the active development of Internet of Things technologies, which make it possible to transition from passive bioreactors to intelligent systems with capabilities

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for continuous monitoring, analysis, and automatic regulation of process parameters (Ray, 2016; Banks et al., 2014; Thangavel et al., 2014). Therefore, the development and investigation of a system combining dynamic mixing and IoT-based monitoring is an important scientific and technical task aimed at improving the reliability, controllability, and productivity of biogas plants. The scientific novelty of this work lies in the proposed integrated approach to controlling the temperature regime of the biomass mixture, based on the combined use of a dynamic mixing device with adjustable blade angles and a vertical movement system, together with an IoT-based multipoint monitoring system. Unlike traditional solutions, the proposed approach implements not only temperature control at individual points, but also real-time analysis of the spatial distribution of the temperature field throughout the entire height of the bioreactor (Zanella et al., 2014). A key feature of the proposed approach is the use of an adaptive control algorithm in which the operating mode of the mixing device changes not only according to the blade inclination angle (0–90°), but also according to the height position of the blades with a discrete step of 20 cm. This makes it possible to create controlled воздействия on different layers of the biomass mixture, starting from the lower zones with increased density and ending with the near-surface layers characterized by active gas release. Unlike conventional systems, where mixing is performed at a fixed point, the proposed scheme provides layer-by-layer mixing and targeted elimination of temperature non-uniformities.

Description of the Dynamic Mixing Device

The proposed dynamic mixing device (Figure 1) is a mechanical system consisting of a rotating shaft with blades, an electric motor, a gearbox, a lifting and lowering mechanism, a threaded section, and a self-cleaning system.

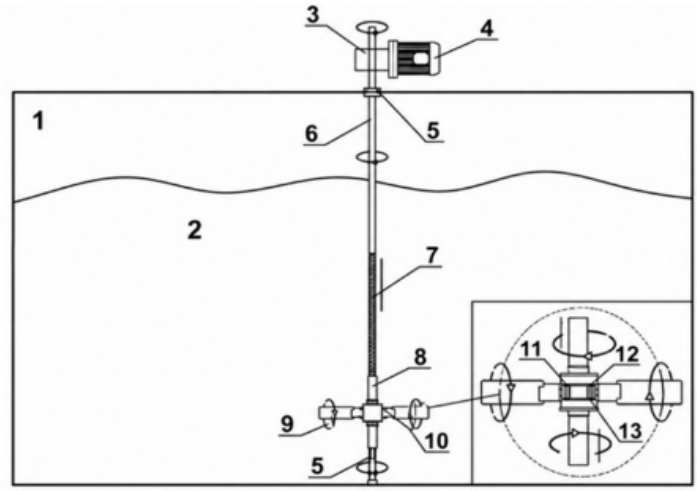


Fig. 1. Structural diagram of the dynamic mixing device installed in the bioreactor

1 - bioreactor body, 2 - biomass mixture, 3 - drive mounting unit, 4 - electric motor with gear reducer, 5 - support and guiding elements, 6 - vertical drive shaft, 7 - threaded section or movable adjustment mechanism, 8 - central mixing mechanism

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unit, 9 -10 blades, 11-12-13 - additional detailed structural elements included in the mixing mechanism.

The design feature of the device is the ability to change the direction of rotation, regulate the immersion depth of the working elements, and adapt the mixing characteristics according to the state of the biomass mixture. The structural diagram (Figure 1) of the dynamic mixing device includes the bioreactor body (1), inside which the biomass mixture (2) is located and serves as the working medium of the anaerobic digestion process. In the upper part of the reactor, a drive mounting unit (3) is installed, on which an electric motor with a gear reducer (4) is mounted, providing rotational motion of the system. The torque from the motor is transmitted through the vertical drive shaft (6), which is stabilized by support and guiding elements (5), ensuring its alignment and reducing vibrations during operation. The shaft includes a threaded section or movable adjustment mechanism (7), allowing the position of the mixing device to be changed along the height of the reactor. In the lower part of the structure, the central mixing mechanism unit (8) is located, to which the side working elements - blades (9, 10) – are attached. These blades create circulation flows in the biomass mixture (2), ensuring intensive mixing and uniform distribution of temperature and substance concentration. Additionally, the mixing mechanism includes detailed structural elements (11, 12, 13), which are responsible for regulating the blade inclination angle and transmitting force from the shaft (6) to the working elements. This makes it possible to change the mixing mode depending on the properties of the biomass mixture (2), such as viscosity and density. Thus, the combined operation of all structural components - the body (1), the drive system (3, 4), the shaft (6), the regulating mechanism (7), and the blade system (9–13) – ensures effective mixing of the biomass mixture (2), improved heat transfer, and increased biogas yield. During operation of the dynamic mixing device, the shaft rotates under the action of the electric motor through the gearbox. The blades mounted on the shaft simultaneously:

- rotate around the axis,
- move along the threaded section of the shaft,
- change their position along the height of the reactor.

At the same time, an additional functional feature of the device is implemented, namely that during operation the blades rotate at a certain angle, which is automatically regulated depending on the biomass load, thereby ensuring effective mixing. This process is caused by the interaction between the gear mechanism and the movement mechanism, in which the resistance of the biomass mixture (its viscosity, density, and non-uniformity) affects the position of the blades and their angle of attack.

The device operates in a self-regulating mode:

- when the viscosity of the medium increases, the blade angle changes to increase the mixing effect;
- when the resistance of the medium decreases, the intensity of the effect is reduced.

The automatic blade inclination angle regulation mechanism is implemented based on monitoring the electric motor current consumption, which serves as a parameter

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characterizing the biomass load. In the initial state, with minimum substrate viscosity and a blade inclination angle of 0°, a base motor current value of approximately 5 A is established. As the viscosity of the biomass mixture increases and the blades enter zones with increased resistance, the motor current gradually rises from 5 A to 10 A, depending on the physic mechanical properties of the medium.

With a further increase in load and when the blade inclination angle reaches its maximum value (up to 90°), a short-term peak current of 12–14 A is observed, indicating the maximum resistance of the medium. The control system is designed to automatically respond to changes in motor current and provides rapid regulation of:

- the blade inclination angle;
- the depth of blade immersion into the biomass mixture.

The blade inclination angle adjustment range is from 0° to 90° and is determined by the current load caused by the substrate viscosity. When the preset threshold current value corresponding to a critical load is reached, the electric motor, designed for reversible operation, automatically stops and switches to rotation in the opposite direction. As a result of this reverse mode, the blade inclination angle changes toward a decrease - from 90° to 0° - which leads to a reduction in medium resistance and restoration of the normal mixing regime.

The blade inclination angle changes automatically due to:

- changes in the load acting on the blades;
- corresponding changes in electric motor current;
- reversible drive control.

Figure 2 illustrates the design of a bioreactor engineered for optimal biomass processing. Key components include a dynamic mixing device (DMD) for vigorous agitation, a comprehensive temperature monitoring system (T1–T4), a level sensor, a pH sensor, and a water jacket for precise thermal control. The DMD's shaft (6), featuring a threaded section (7) and a blade mechanism (8) positioned at the reactor's base, drives active biomass mixing. This rotational action creates upward and downward currents, establishing a consistent circulation pattern throughout the entire reactor volume. Consequently, stagnant zones are eliminated, and the substrate is uniformly distributed. The dynamic mixing process also facilitates intensive heat transfer from the water jacket (hot water inlet – 18, return water outlet – 17), ensuring a uniform temperature profile across the reactor's height. Data from the temperature sensors (9–12) validates the significant reduction in the temperature gradient between the upper and lower sections. Furthermore, mass transfer is enhanced: biogas bubbles separate more efficiently from the liquid phase and rise rapidly towards the gas outlet (15). This leads to an increased biogas release rate and prevents gas buildup in the lower reactor layers. The integrated pH sensor (13) and level sensor (14) allow for continuous monitoring of crucial digestion parameters, thereby guaranteeing optimal conditions for methanogenesis. The biomass discharge outlet (17), located at the reactor's bottom, enables the removal of processed substrate and ensures sustained system performance.

The implementation of the dynamic mixing device leads to:

- uniform flow distribution throughout the reactor.

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- mitigation of temperature and concentration gradients.
- enhanced heat and mass transfer.
- improved rate and stability of biogas production.

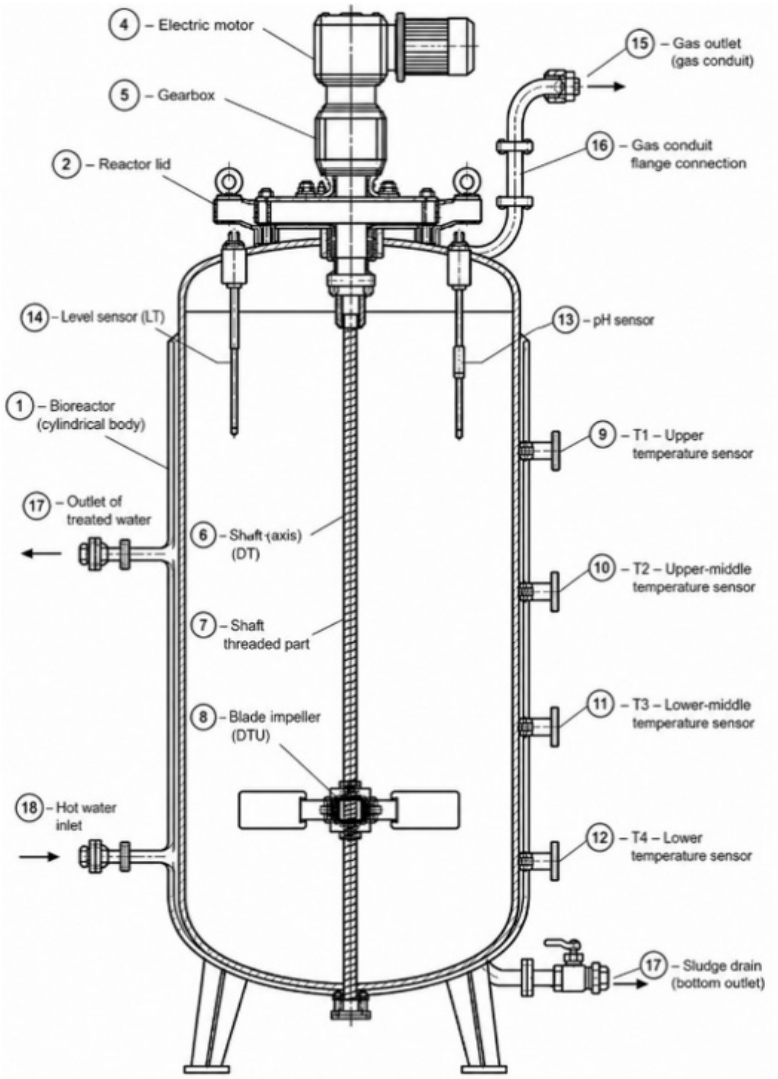


Fig. 2. Bioreactor with a Dynamic Mixing Device

This study addresses several interrelated objectives to achieve the stated goal. It begins with an analysis of current bioreactor mixing methodologies, specifically examining their effect on the thermal uniformity of the medium. Following this, a dynamic mixing device is engineered to promote more effective heat distribution and eradicate stagnant zones. An IoT-based monitoring system, built on the ESP32 platform, is then established for comprehensive multipoint temperature measurement and the real-time acquisition of operational data. Additionally, the research explores the temperature distribution within the biomass mixture under diverse reactor conditions, quantifies the impact of mixing on biogas output, and formulates an intelligent control

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algorithm for adaptive activation and regulation of the mixing process based on the system's current state.

This principle ensures self-regulating adaptation of the device to changing properties of the biomass mixture without the need for external operator intervention. The use of the threaded section and the vertical movement mechanism makes it possible to change the working impact zone inside the reactor, which is especially important in the case of non-uniform distribution of temperature and substrate density along the reactor height. The self-cleaning system prevents the accumulation of deposits and ensures stable operation of the device under long-term operating conditions. Due to the formation of directed and turbulent flows, the proposed device contributes to the elimination of stagnant zones, equalization of temperature throughout the reactor volume, and intensification of heat transfer. As a result, more uniform mixing of the biomass mixture is achieved, the load on the drive system is reduced, conditions for biochemical processes are improved, and the overall efficiency of the bioreactor is increased. The novelty also lies in the development of an intelligent mixing control algorithm in which the motion parameters (blade angle α and height h) change depending on the magnitude of the temperature gradient and the local state of the biomass mixture (Zhang et al., 2019; Li et al., 2020). In mathematical form, this can be represented as follows:

$$\alpha = f(\nabla T),\ h = f(\nabla T, z) \tag{1}$$

where ∇T - is the temperature gradient, and z - is the coordinate along the height of the reactor.

This approach makes it possible not only to mix the substrate at predetermined time intervals, but also to purposefully influence zones with unfavorable thermal conditions, such as overheated or cooled regions. When significant temperature deviations are detected, the system automatically changes the position of the device and the blade angle, intensifying the mixing process specifically in the problematic areas.

Change in Biomass Mixing with Variation of Blade Angle from 0° to 90°

When the inclination angle of the blades of the dynamic mixing device changes from 0° to 90°, a gradual change occurs in the nature of the blade interaction with the biomass mixture. At small angles, the blades create low resistance to the flow; therefore, the mixing process occurs gently, and the electric motor current consumption remains close to its minimum value. As the inclination angle increases, the interaction area between the blade and the biomass mixture becomes larger, which leads to intensified circulation flows, increased shear impact, and more effective elimination of stagnant zones. At blade angles of 60–75°, the mixing process becomes most efficient, since active movement of the biomass is ensured in both the radial and vertical directions. When the angle reaches 90°, the resistance of the biomass mixture becomes maximal, and the motor current temporarily rises to its peak value. Therefore, this operating

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mode is advisable only under conditions of high viscosity or when it is necessary to break up dense layers.

The blade inclination angle is denoted as:

$$\alpha = 0 \ldots 90°$$

where α - is the blade inclination angle relative to the horizontal position.

The effective interaction area of the blade with the biomass mixture can be expressed as:

$$A_{eff} = A \cdot sin\alpha \tag{2}$$

where: A_{eff} - is the effective interaction area of the blade, A- is the total blade area, α - is the blade inclination angle.

As the inclination angle increases, the hydrodynamic resistance also increases:

$$F = C_d \cdot \frac{\rho v^2}{2} \cdot A_{eff} \tag{3}$$

or:

$$F = C_d \cdot \frac{\rho v^2}{2} \cdot A_{eff} \cdot \sin(\alpha) \tag{4}$$

where: F - is the resistance force of the biomass mixture, C_d - is the drag coefficient, ρ - is the density of the biomass mixture, v - is the blade movement velocity, A - is the blade area.

The torque on the shaft can be determined as:

$$M = F \cdot r \tag{5}$$

where: M - is the torque, r - is the radius of the blade position.

Then, the dependence of the torque on the blade angle is given by:

$$M(\alpha) = C_d \cdot \frac{\rho v^2}{2} \cdot A_{eff} \cdot r \cdot \sin(\alpha) \tag{6}$$

The current consumption of an electric motor can be roughly expressed in terms of load torque:

$$I(\alpha) = I_0 + k \cdot \sin(\alpha) \tag{7}$$

where: I_0 - is the current of the idle or minimum mode, k - is the coefficient of coupling between the torque and the current of the motor.

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For a practical description, you can use a simplified dependency:

$$I(\alpha) = I_0 + (I_{max} - I_0) \cdot \sin(\alpha) \quad (8)$$

If you accept:

$$I_0 = 5\ A, I_{max} = 10\ A$$

then:

$$I(\alpha) = 5 + 5 \cdot \sin(\alpha)$$

Table 1. Changes in parameters when changing the angle of the blades.

Blade angle, deg	α	motor current, A	Mixing Pattern
0°	0	5.00	Minimal resistance, weak mixing
15°	0.259	6.30	Initial Flow Gain
30°	0.500	7.50	Moderate stirring
45°	0.707	8.54	Active Stirring
60°	0.866	9.33	Intensive circulation of the biomass mixture
75°	0.966	9.83	Very strong mixing, destruction of stagnant zones
90°	1.000	10.00	Maximum load, maximum resistance

When a short-term angle of 90° is reached in the high viscosity zone, the current can increase to a peak value:

$$I_{peak} = 12 \ldots 14\ A$$

Changing the operation of the stirring device during lifting in 20 cm increments

When the mixing device is lifted along the vertical axis with a step of 20 cm, the blades are sequentially affected by different layers of the biomass mixture. This mode allows to destroy dead zones not only in the lower part of the reactor, but also along the entire height of the working medium. As the blades rise, they move the dense layers upwards, improve the distribution of organic particles and increase the release of biogas. which are then combined into a common volume flow. This increases the uniformity of mixing, reduces the settling of solids and improves the contact of microorganisms with the culture medium. The height of the agitator position can be set as:

$$h_i = h_0 + i \cdot \Delta h \quad (9)$$

where: h_i - position of the blades at the i-th level, m; h_0 - initial height from the bottom of the reactor, m; Δh=0,20 м - lifting step; i=0,1,2,3,…,n - step number.

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If the working height of the biomass mixture is equal to (H), the number of positions shall be determined:

$$n = \frac{H - h_0}{\Delta h} \tag{10}$$

For example, if the height of the biomass mixture: H = 2 m, h_0 = 0,20 м
Then: $n = \frac{2-0,2}{0.2.} = 9$
That is, the device can occupy 10 positions: from 0.20 m to 2.00 m.

Relation of vertical movement of the device to the angle of inclination of the blades

When lifting the device, the angle of the blades can change depending on the resistance of the biomass mixture:

$$\alpha(h) = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot \frac{I(h) - I_0}{I_{max} - I_0} \tag{11}$$

where: *α(h)*-is the angle of the blades at a given height; $\alpha_{min} = 0°; \alpha_{min} = 90°$; $I(h)$ -motorcurrentatagivenaltitude. $I_0 = 5\ A; I_{max} = 10\ A$
If the biomass mixture is more viscous at a certain height, the motor current increases, and the system automatically increases the angle of inclination of the blades. If the resistance decreases, the angle of the blades is reduced so as not to create an unnecessary load on the engine.

Thus, changing the angle of inclination of the blades from 0° to 90° allows you to adjust the intensity of mixing of the biomass mixture depending on its viscosity and resistance. At small angles, the load on the motor is minimal, but the mixing efficiency is also low. With an increase in the angle to 45–75°, more pronounced circulation flows are formed, which provide an even distribution of organic mass and activation of gas emissions. The angle of 90° corresponds to the maximum resistance of the biomass mixture and is used as a short-term mode for compaction or increased viscosity of the substrate. The control of the angle of the blades by changing the motor current allows you to automatically adapt the operation of the mixing device to the real state of the biomass in the reactor. Thus, the lifting of the mixing device with a step of 20 cm ensures the layer-by-layer treatment of the biomass mixture along the entire height of the reactor. In the lower zone, the device destroys dense sludge, in the middle zone it forms stable circulation flows, and in the upper zone it contributes to the active release of biogas. This method of mixing is more efficient than the usual stationary arrangement of the blades, since the effect is not at one point, but throughout the entire volume of the reactor. Lift control, combined with changing the angle of the blades, adapts the operation of the device to the viscosity of the biomass and reduces the risk of stagnant zones. In addition, the paper shows that the combination of vertical movement of the device and regulation of the blade angle leads to the formation of

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more intense circulation and turbulent flows throughout the reactor volume (Wu, 2010; Stroot et al., 2001). This ensures a reduction in temperature gradients, improved heat exchange and an increase in the homogeneity of the biomass mixture, which in turn contributes to an increase in the efficiency of anaerobic digestion and the stability of the biogas formation process.

IoT Monitoring and Control System

The developed IoT monitoring and control system is built on the basis of the ESP32 microcontroller, which acts as a central node for collecting, processing and transmitting data (Al-Fuqaha et al., 2015; Li et al., 2020). The system includes temperature sensors located on several levels inside the bioreactor, as well as additional humidity, gas leakage and pressure sensors that allow monitoring both the internal state of the environment and the parameters of safe operation of the facility. wireless communication channels using Wi-Fi and the MQTT protocol (Banks et al., 2014; Thangavel et al., 2014), which provides the possibility of remote monitoring and integration with external information systems.

To visualize the parameters, a web panel is used, which displays current temperature values, heat field distribution, actuator status, and alarm messages. Functionally, the system provides real-time data collection, analysis of temperature deviations, automatic control of the mixing device and transmission of notifications in case of emergency situations (Ray, 2016; Calise, 2020). The IoT component not only increases the information content of process monitoring, but also creates the basis for intelligent control of the bioreactor. Figure 3 shows an intelligent control system for the process of mixing the biomass mixture in the bioreactor, equipped with multipoint temperature monitoring. Inside the reactor vessel, a dynamic mixing device with a vertical shaft and adjustable blades is installed, which ensures the formation of circulation flows throughout the biomass mixture volume. In the upper part of the reactor, there is an active release of biogas, which indicates the intensive course of anaerobic processes fermentation. Four temperature sensors are installed to monitor the temperature regime by the height of the reactor: the upper T1 sensor, the middle upper T2 sensor, the middle lower T3 sensor and the lower T4 sensor. These sensors are placed at different levels (H1–H4), which allows obtaining information about the spatial distribution of temperature inside the bioreactor. Signals from the sensors are transmitted to the data acquisition and processing system based on the ESP32 microcontroller, where their primary processing is carried out. The data is then transmitted wirelessly (WiFi/MQTT) to the cloud system and displayed in the web interface as a real-time temperature field. Based on the analysis of the data obtained, the presence of temperature gradients and inhomogeneities in the biomass mixture is determined. If deviations are detected, the system automatically adjusts the agitator by changing the blade angle and the height of the mechanism. The presented system provides adaptive control of the mixing process, which contributes to the equalization of the temperature field, increasing the homogeneity of the biomass mixture and increasing the efficiency of biogas production.

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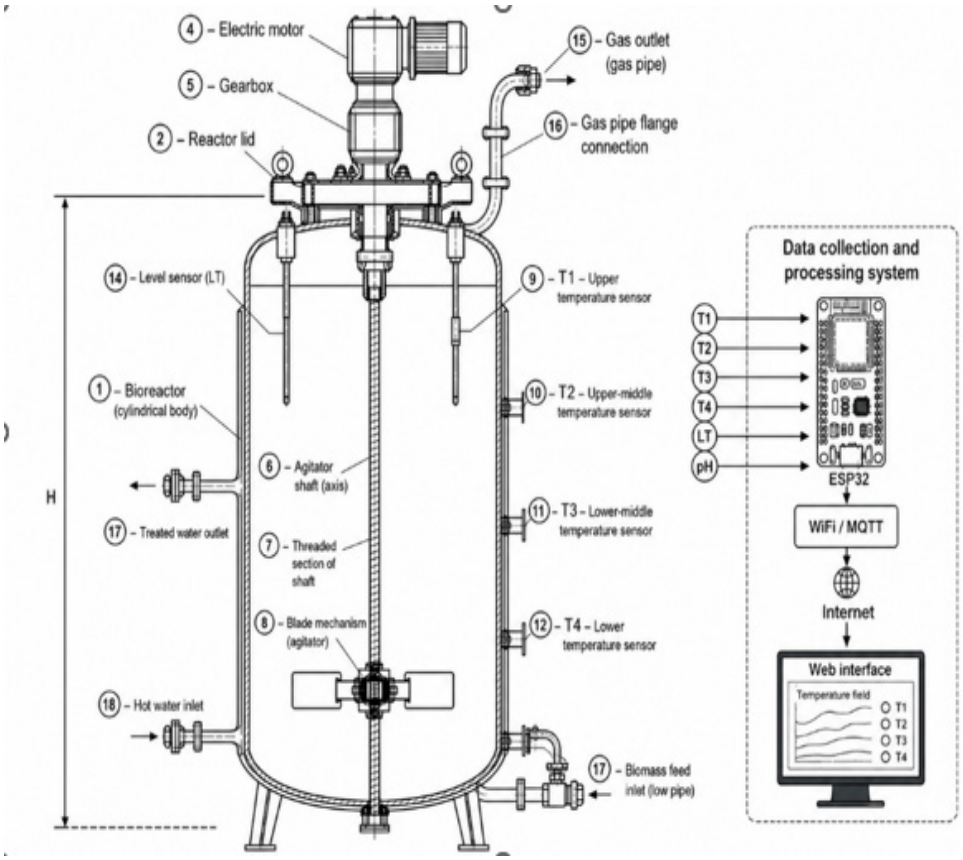


Fig. 3. IoT System Diagram for Bioreactor

Figure 4 shows a structural diagram of the algorithm for controlling the mixing of a biomass mixture in a bioreactor, implemented on the basis of IoT technologies and temperature field analysis. The algorithm consists of sequential steps that provide data collection, processing, analysis, and adaptive control of mixing parameters. In the first step, data is collected from the T1-T4 temperature sensors located at the height of the reactor, after which the information is transmitted via the ESP32 microcontroller via WiFi/MQTT to the cloud system and displayed in the web interface in real time. At the second stage, data processing is carried out, including the formation of a temperature field and the calculation of the temperature gradient as the difference between the temperature values along the height of the reactor. And the third stage is the analysis of the state of the system, which determines the presence of a temperature imbalance based on a comparison of the current gradient with the permissible value. If the threshold value is exceeded, the intensive mixing mode is activated, otherwise the current operating mode is maintained blade inclination in the range from 0° to 90° depending on the value of the local temperature gradient. Next, control actions are performed, including moving the device in height and changing the angle of the blades. After the control actions are performed, the result is monitored for a specified time, then the data is re-collected and the effectiveness of the regulation is checked. If a uniform temperature

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distribution is achieved, the system switches to the minimum mode, and if deviations persist, the control cycle is repeated. As a result of the algorithm, temperature gradients are reduced, the temperature field is equalized by the height of the reactor, the anaerobic digestion process is stabilized, the intensity of biogas formation is increased and energy consumption is reduced. Event logging is also provided, recording system parameters such as time, agitator height, blade angle, and pre- and post-adjustment temperatures. The experimental study was carried out on a bioreactor in several modes of operation, which made it possible to compare the effectiveness of different methods of influencing the biomass mixture. Three main modes were considered: no mixing, conventional mechanical mixing and dynamic mixing using the proposed device. The study was carried out in two characteristic temperature ranges: mesophilic mode at a temperature of about 35 °C and thermophilic mode at a temperature of about 55 °C. Comparison of the data obtained made it possible to determine the degree of temperature homogeneity of the medium, to establish the influence of the type of mixing on the dynamics of the process and to assess the effectiveness of the proposed system in conditions close to real operation.

Results and discussion.

As a result of the application of the proposed algorithm, significant improvements were obtained in the temperature distribution and efficiency of the digestion process. The analysis was carried out using three-dimensional graphs and a table reflecting the dependence of temperature on reactor altitude and time. Analysis of the results presented in Table 2 shows that the change in the height of the dynamic mixing device (DPC) significantly affects the nature of mixing and the distribution of biomass mixture flows inside the bioreactor. At the initial position of the blades at a height of 0.20 m, the impact is concentrated in the lower zone of the reactor, where the dense sedimentary layer is destroyed and the accumulation of heavy organic deposits is prevented. This helps to reduce the local compaction of the substrate and improve the access of microorganisms to organic substances. When the blades rise to 0.40 m, the impact zone shifts to the lower-middle area of the reactor. In this mode, there is an active uplift of heavy particles, which reduces the probability of the formation of stagnant zones and improves the circulation of biomass. At a height of 0.60 m, the vertical flow increases, which contributes to a more intensive heat transfer and distribution of organic components throughout the reactor volume. where the main mixing of the biomass mixture is carried out.

In this area, the most stable flow distribution is achieved, temperature heterogeneity is reduced (Ward et al., 2008; Lindmark et al., 2014; Wu, 2010) and the uniformity of anaerobic digestion is increased. With a further rise of up to 1.00 m, the device acts on the central zone of the reactor, ensuring the equalization of the concentration of organic substances and increasing the efficiency of biochemical processes. At a height of 1.20 m, the impact zone passes into the central-upper part of the reactor.

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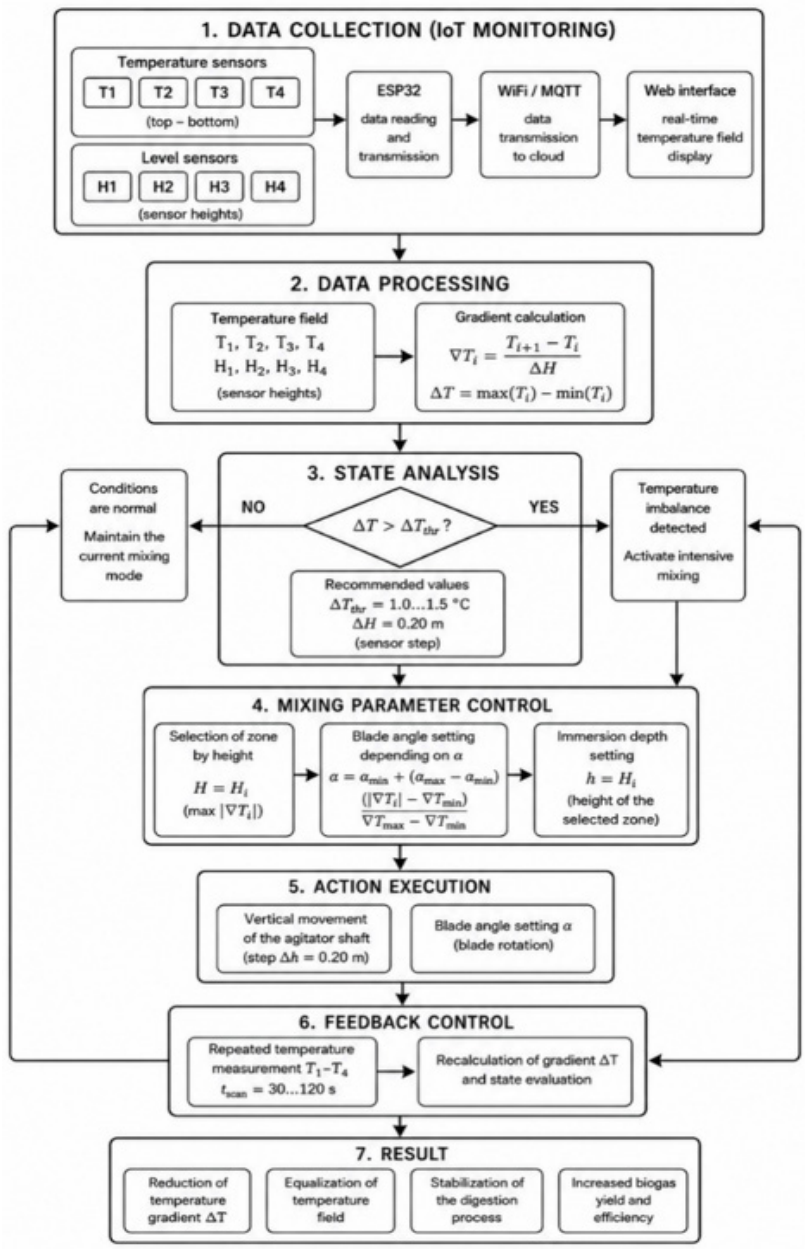


Fig. 4. Structural diagram of the algorithm for controlling the mixing of a biomass mixture in a bioreactor

Here there is an increase in the circulation of the biomass mixture and an acceleration of the movement of gas-liquid flows. At the 1.40 m position, the blades work in the upper zone, providing biomass to the area of active gas release, which improves the process of separating biogas bubbles from the substrate. When the DMD rises to 1.60 m, the release of gas bubbles is intensified (Wu, 2010; Stroot et al., 2001), which is associated with an increase in turbulence in the upper layers of the reactor. This helps to reduce gas accumulation within the biomass and reduce local

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oversaturation zones. At a height of 1.80 m, the device acts on the near-surface area, ensuring the removal of accumulated gas and preventing the formation of stable gas pockets. The maximum position of the blades at a height of 2.00 m corresponds to the surface zone of the reactor. In this mode, the most intense gas emission and destruction of surface foam are observed. This improves biogas yield, stabilizes reactor operation and reduces the risk of clogging the top of the system. The results obtained confirm that the sequential change in the DMD height makes it possible to effectively control hydrodynamic flows, biomass distribution and the process of gas formation throughout the bioreactor.

Table 2. Change of the impact zone when lifting the DMD with a step of 20 cm

Step	Blade height, m	Height, cm	Area of Exposure	Mixing Pattern
0	0,20	20	Lower Zone	Destruction of sediment and dense layer
1	0,40	40	Lower - middle zone	Lifting of heavy particles upwards
2	0,60	60	Lower-middle zone	Vertical Flow Reinforcement
3	0,80	80	Middle Zone	Basic mixing of the biomass mixture
4	1,00	100	Central Zone	Leveling the concentration of organic matter
5	1,20	120	Central-upper zone	Increased circulation
6	1,40	140	Upper zone	Biomass supply to the gas release zone
7	1,60	160	Upper zone	Gas bubble release stimulation
8	1,80	180	Near-surface zone	Removal of accumulated gas
9	2,00	200	Surface Zone	Maximum Gassing and Foam Breakdown

The graph in Figure 5 shows the initial state of the system without intelligent management. The graph shows a pronounced temperature stratification: the temperature is higher in the upper part of the reactor, and much lower in the lower part. The graph surface has a slope and an inhomogeneous structure, which indicates weak mixing and poor heat transfer.

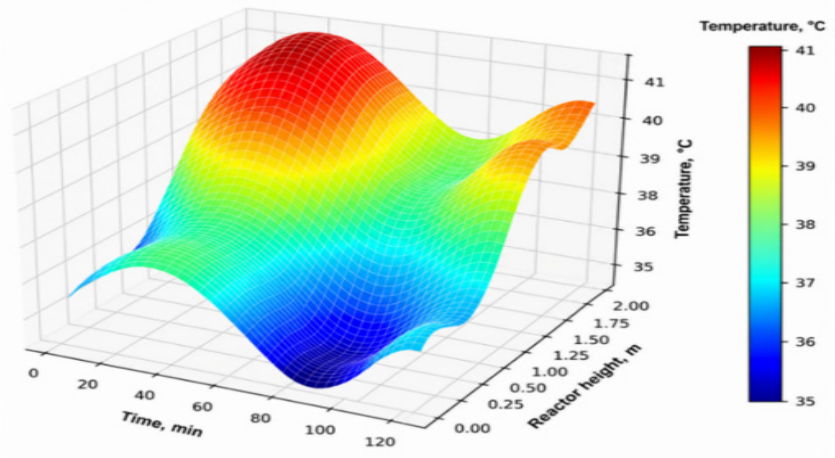


Fig. 5. Initial state of the system without intelligent control

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The graph in Figure 6 shows the state after the algorithm has been applied. The temperature surface becomes more even, the differences between the layers are reduced, and the temperature distribution along the height of the reactor is evened out. This indicates effective mixing and the elimination of stagnant zones.

Figure 7 shows the dynamics of the temperature gradient over time. At the initial moment, there is a high temperature range, but as the algorithm works, the gradient gradually decreases and stabilizes. The surface of the graph becomes more uniform, which indicates the achievement of a stable regime. In addition, it has been established that a decrease in the temperature gradient leads to improved heat exchange and a more uniform distribution of microorganisms in the biomass mixture.

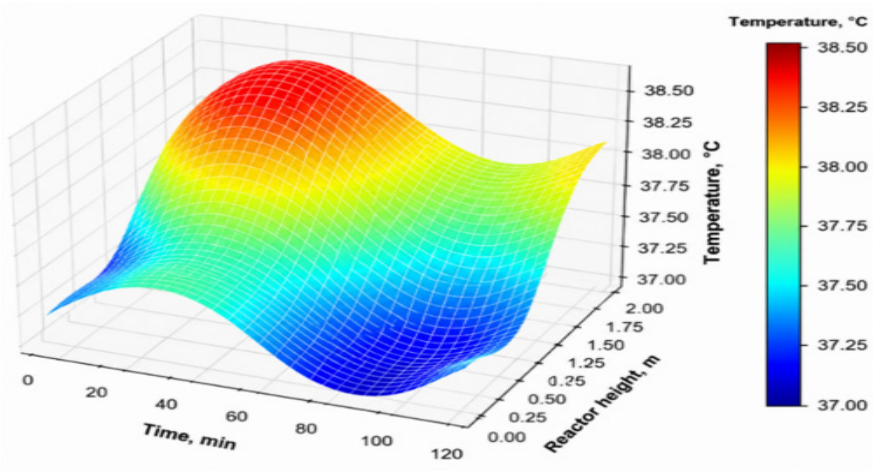


Fig. 6. Graph of the demonstration of the state after applying the algorithm

This contributes to an increase in the intensity of anaerobic digestion and an increase in biogas yield. The results of modeling and analysis confirm the effectiveness of the proposed algorithm. The use of adaptive mixing control not only stabilizes the temperature regime, but also improves the overall energy efficiency of the system.

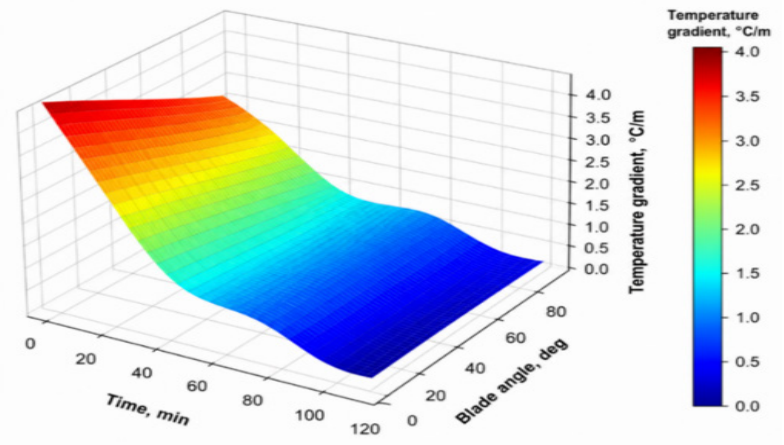
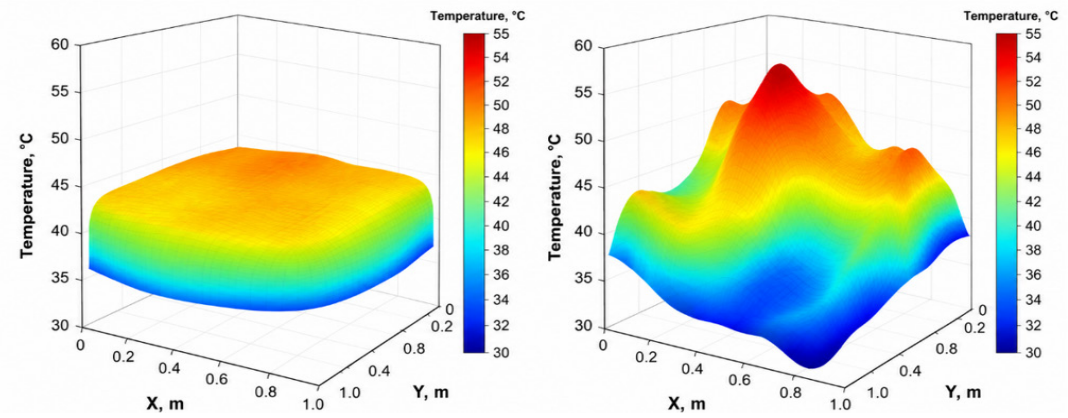


Fig. 7. Graph of reflection of the dynamics of temperature changes gradient in time.

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Studies have shown that in the absence of mixing, pronounced temperature gradients are formed inside the bioreactor, and the difference between individual zones can reach 8–10 °C. Such unevenness adversely affects the stability of methanogenesis and reduces the efficiency of the use of the reaction volume, which is consistent with the data of other studies (Ward et al., 2008; Lindmark et al., 2014). When using a dynamic mixing device, the temperature field pattern changes significantly. Due to the active movement of the biomass mixture and the destruction of stagnant zones, a more uniform distribution of heat is ensured, and the temperature deviation along the volume of the reactor does not exceed 1–2 °C (Wu, 2010; Stroot et al., 2001). This indicates the high efficiency of the proposed design in ensuring thermal homogeneity and creating optimal conditions for anaerobic digestion (Chen et al., 2008; Karim et al., 2005).



a) with the use of DMD. b) with a conventional reaming device.

Fig. 8. Comparison of the temperature field in a bioreactor when using a DMD and a conventional mixing device

Figure 8 shows a comparative three-dimensional temperature distribution in a bioreactor under two mixing modes: with the use of a dynamic mixing device (DMD) and with a conventional mixing device. Figure 8(a) shows the temperature field when the DMD is operating at a speed of 30 rpm. The temperature varies in a narrow range (approximately 40-45 °C), without sudden local overheating or cooling zones. This indicates efficient mixing, in which there is intensive heat transfer and equalization of the temperature field. Figure 8 (b) shows the temperature distribution when using a conventional agitator. The surface has pronounced irregularities and peaks, which indicates the presence of significant temperature inhomogeneities. Temperatures vary over a wider range (30 to 55 °C), with local overheating zones (up to 55 °C) and low temperature zones (around 30 to 35 °C). This indicates insufficient mixing efficiency and the presence of stagnant areas.

A comparison of the two modes shows that the use of DMD leads to:

- reducing temperature gradients,
- elimination of local overheating,

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- formation of a more homogeneous structure of the biomass mixture,
- increasing the efficiency of heat exchange.

The use of a dynamic agitator provides a more uniform temperature distribution over the volume of the bioreactor compared to traditional mixing systems, which contributes to increasing the stability and efficiency of the biogas formation process (Lindmark et al., 2014; Wu, 2010; Weiland, 2010).

In the course of the study, additional results were obtained using the MATLAB environment and the Simulink module, which made it possible to simulate the dynamics of the temperature field and mixing processes in the bioreactor. Simulations have shown that in the absence of mixing, pronounced temperature gradients of up to 8–10 °C are formed, while when using a dynamic mixing device, they are reduced to 1–2 °C throughout the reactor volume. The results of the simulation also confirmed that adaptive change in the angle of inclination of the blades in the range of 60-75° provides the most uniform temperature distribution and the lowest energy costs. In addition, 3D models of temperature and flow rate distribution were built at MATLAB, demonstrating the elimination of stagnant zones and the formation of stable circulation flows. The data obtained are in good agreement with the experimental results and confirm the effectiveness of the proposed method of dynamic mixing and intelligent control.

The results obtained confirm that the improvement of temperature uniformity has a direct impact on the kinetics of the digestion process. With the use of dynamic mixing, there is an acceleration of the decomposition of the organic substrate, an increase in the activity of microorganisms and a reduction in the overall processing time. This is due to the fact that a uniform temperature field contributes to maintaining a favorable environment for the life of methanogenic microflora and reduces the likelihood of zones in which biological activity is suppressed. In addition, more intensive heat and mass transfer contributes to better contact of microorganisms with organic matter, which increases the completeness of substrate processing. Thus, dynamic mixing has a positive effect not only on the physical state of the biomass mixture, but also on the biochemical efficiency of the entire process. The use of an IoT monitoring system made it possible to provide continuous monitoring of the process in real time and improve the accuracy of the bioreactor control. Thanks to multi-point temperature measurement, it is possible to detect deviations in heat distribution in a timely manner and react quickly to them by switching on agitation. This approach ensures the transition from periodic monitoring to continuous digital process support. An additional advantage of the system is the ability to automate decision-making. Based on the data coming from the sensors, the controller analyzes the state of the biomass mixture and activates the actuators only when it is really needed. This makes it possible to increase energy efficiency, reduce excessive equipment operation, and at the same time improve the stability of the digestion process (Ray, 2016; Al-Fuqaha et al., 2015). The combined use of a dynamic mixing device and IoT monitoring has shown that such a system provides a noticeable increase in the overall efficiency of the bioreactor. According to the results of the study, an increase in biogas yield within 15–25% was established, a

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decrease in energy consumption due to a more rational mode of operation of actuators and an increase in the stability of the technological process. These results indicate that the proposed system is not limited to improving the local characteristics of the thermal regime, but has a complex positive effect on the functioning of the entire biogas plant. Increasing the stability and controllability of the process creates conditions for the practical implementation of the developed solution both at small farm plants and at industrial biogas plants (Mertins et al., 2021; Céileachair et al., 2023).

Conclusion.

The obtained results demonstrate that the integration of a dynamic agitator with an intelligent IoT monitoring system exerts a complex influence on the efficiency of anaerobic bioreactors. A key limitation in conventional systems is significant temperature stratification along the reactor's height, leading to gradients of 8–10 °C. This stratification impedes methanogenic microbial activity and fosters the development of stagnant zones. The introduction of dynamic mixing fundamentally reconfigures temperature distribution by generating directed circulation and turbulent flows. These phenomena ensure vigorous movement of the biomass mixture throughout the reactor, thereby reducing temperature deviations to an optimal range of 1–2 °C for methanogenesis. The adaptive control of the blade angle, adjustable from 0° to 90°, plays a pivotal role in process optimization. At lower angles, gentle mixing with reduced energy expenditure is achieved. Conversely, increasing the angle enhances hydrodynamic resistance and intensifies the process. The most advantageous operational mode is observed within the 60–75° range, striking an optimal balance between energy consumption and mixing intensity. A temporary adjustment to 90° is recommended for highly viscous substrates or when dense layers require disruption. Furthermore, the vertical displacement of the device, with a step of 0.20 m, imparts a layer-by-layer effect on the biomass mixture. This action dislodges precipitates in the lower zone, establishes stable circulation flows in the middle zone, and intensifies gas release in the upper zone. The ESP32-based IoT monitoring system facilitates multi-point temperature measurement, real-time data transmission, and the execution of adaptive control algorithms. This transition from periodic monitoring to continuous, intelligent process management allows agitation to be activated only when permissible temperature gradients are exceeded. Such a targeted approach minimizes energy consumption (Calise et al., 2020; Mertins et al., 2021) and enhances overall system efficiency. From a biochemical perspective, diminished temperature heterogeneity promotes increased activity of methanogenic microflora (Khan et al., 2017; Chen et al., 2008), accelerates organic substrate decomposition, and shortens digestion time. Enhanced heat and mass transfer ensures more effective contact between microorganisms and the nutrient medium, leading to a more complete processing of organic matter. Consequently, the synergistic effects of dynamic mixing and intelligent monitoring can lead to a 15–25% increase in biogas yields, coupled with reduced operational costs and mitigated risks associated with process parameter variability. The practical significance of this research lies in its potential for widespread adoption across biogas plants of varying scales, from farm-level operations to industrial complexes. The utilization

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of readily available components, wireless communication technologies, and adaptive control algorithms ensures straightforward implementation, scalability, and versatility. This system is particularly valuable for facilities requiring remote monitoring, where minimizing personnel intervention and maximizing technological process reliability are paramount. The integration of the dynamic mixing device with the IoT control system represents a significant advancement in anaerobic bioreactor management, ensuring process stability, enhanced energy efficiency, and reduced operational risks».

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ХАЛЫҚАРАЛЫҚ АҚПАРАТТЫҚ ЖӘНЕ КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАР ЖУРНАЛЫ

МЕЖДУНАРОДНЫЙ ЖУРНАЛ ИНФОРМАЦИОННЫХ И КОММУНИКАЦИОННЫХ ТЕХНОЛОГИЙ

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