

Analysis of technologies for biogas production through filtration and utilisation of wastewater in an urban environment

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ABSTRACT

The aim of the study was to establish the relationship between indicators of preliminary treatment, fermentation, and membrane processing of wastewater and the final level of its environmental safety. The study employed gravimetric, spectrophotometric, chromatographic, titrimetric, microbiological, and membrane-filtration methods using accredited laboratory instruments to assess the physico-chemical, gas-related, and environmental parameters of wastewater. Pre-filtration ensured a substantial reduction in pollutants: suspended solids decreased from 320 to 145 mg/L (-54.7%), turbidity from 68 to 24 NTU (-64.7%), biochemical oxygen demand from 185 to 128 mg O₂/L (-30.8%), and chemical oxygen demand from 420 to 295 mg O₂/L (-29.8%). The biogas formation potential increased from 0.21 to 0.24 m³/kg of removed chemical oxygen demand (+14.3%). In bioreactors, the thermophilic regime (+55 °C) demonstrated higher values: the methane CH₄ fraction reached 66–71%, biogas yield amounted to 0.31–0.36 m³/kg, and hydrogen sulphide H₂S decreased to 110–150 ppm. Membrane post-treatment reduced total organic carbon from 22–28 to 4–6 mg/L, adsorbable organic matter from 2.8–3.4 to 0.4–0.6 mg/L, and the silt density index (SDI) from 6.5–7.2 to 1.2–1.6 units. After complete treatment, nitrites decreased to 0.08–0.12 mg/L, microplastics to 110–180 particles/L, and residual toxicity increased to 82–91% survival, which confirms the environmental safety of the obtained permeate. The results obtained are of practical value for engineers of wastewater treatment facilities and environmental services, who may apply them to optimise filtration, biogas fermentation, and membrane post-treatment of wastewater.

Keywords: membrane post-treatment, organic compounds, anaerobic digestion, adsorbable organic matter, microplastics.

INTRODUCTION

The relevance of the present study is determined by the increasing impact of municipal and industrial wastewater on the aquatic ecosystems of large cities, where conventional treatment technologies no longer ensure an adequate level of removal of organic pollutants, nutrients, microplastics, and toxicological markers. Urbanisation growth, increased water consumption, and changes in the

composition of household chemicals lead to the formation of persistent complex pollutants capable of passing through standard stages of mechanical and biological treatment [1]. Under these conditions, the application of membrane processes becomes a key direction for enhancing post-treatment efficiency and achieving stable water quality that meets contemporary environmental requirements. The problem addressed in this study is associated with the limited effectiveness of traditional

methods in removing fine-dispersed, colloidal, and biologically active components that determine residual toxicity, microbiological risks, and the environmental impact of treated wastewater [2, 3]. Additional complexity arises from changes in the chemical composition of wastewater, high concentrations of surfactants, petroleum products, and synthetic organic compounds that interact with one another and form persistent contaminant complexes. As a result, there is a need for a comprehensive assessment of membrane post-treatment processes, making it possible to determine the dynamics of changes in key water quality parameters and to establish the degree of reduction in environmental pressure on water bodies.

In the context of studies devoted to membrane-based enhancement of the methane fraction, Kaipova et al. [4] examined modern solutions for biogas purification using highly selective membranes. It was shown that the efficiency of the processes depended on the preliminary removal of colloidal impurities. Taking into account thermophilic organic degradation processes investigated by Bayazitova et al. [5], the influence of temperature on the characteristics of liquid fermentation products was analysed. It was recorded that changes in substrate composition determined the subsequent degree of its stabilisation. Within the framework of studying the microbiological transformation of sludge, Kominko et al. [6] investigated the conversion of urban sewage sludge into organo-mineral products. It was established that changes in biochemical structure influenced the efficiency of subsequent water treatment. Based on the analysis of the biogas sector in Kazakhstan presented by Abilmazhinov et al. [7], the conditions for the implementation of biogas installations were assessed. It was established that climatic constraints and sensitivity to feedstock composition reduced system operational stability.

In assessing lost biogas potential, Yerassyl et al. [8] performed a quantitative analysis of organic waste from livestock and poultry farming. It was shown that incomplete involvement of feedstock in anaerobic digestion led to significant energy losses. In studies on the digitalisation of biogas processes, Amirkhanov et al. [9] analysed the application of a digital twin of a modular bioreactor. It was confirmed that real-time control increased the stability of methanogenesis under changing substrate composition.

Within the technical and economic assessment of the energy intensity of wastewater, Freitas et al. [10] considered the potential use of biogas for the energy supply of medium-sized cities. It was shown that system stability depended on the degree of substrate purification. From the perspective of using biogas as a transport fuel, Un [11] analysed the energy potential and environmental advantages of gaseous fractions. It was revealed that the impact of emissions was determined by the quality of preliminary gas preparation. In the direction of determining the environmental footprint of cogeneration systems, Ciula et al. [12] investigated the influence of biogas purification depth on pollution per unit of generated energy. The study confirmed that improving the purification procedure led to lower levels of contamination overall. Werkneh [13] gathered information on the toxicity of biogas pollutants and the methods used to get rid of them, taking into account the most common pollutants and the risks they pose. The composition of these contaminants has a major impact on the choice of purification methods [14–16].

Miyawaki et al. [17] examined the correlation between biogas production and biotechnological processes, focusing on the synergistic impacts of wastewater treatment and purified biogas on the promotion of microalgal development. Their results showed that changes in the gaseous environment had a big effect on biomass productivity. Castellanos-Sánchez et al. [18] performed a comprehensive investigation of modern techniques aimed at improving biogas purification. Adding membrane stages to the process made it much more selective. Although there is a lot of information, we still need to do more research to fully understand how different stages, like preliminary filtration, biogas fermentation, membrane post-treatment, and the overall environmental impact of wastewater treatment, are all connected within a single technological framework.

This study aimed to thoroughly evaluate wastewater quality, the effectiveness of biogas fermentation, and the results of membrane post-treatment. It also looked at how these procedures together affect the safety of the treated water for the environment. The objectives of the study were to assess changes in the physico-chemical and microbiological characteristics of wastewater at the stages of preliminary filtration, fermentation, and membrane post-treatment; to determine biogas yield and composition under

different technological regimes; and to establish the level of environmental efficiency of the final effluent based on integrated chemical, toxicological, and biological indicators.

MATERIALS AND METHODS

The studies were carried out in 2025 at Abay Myrzakhmetov Kokshetau University (Akmola Region, city of Kokshetau) within the framework of a grant-funded project of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan for 2025–2027, IRN AR 26194475, entitled “An Innovative Approach to Biogas Production through Filtration and Utilisation of Wastewater of the City of Kokshetau”, using pilot-scale biogas fermentation and membrane post-treatment installations. Water quality analyses, as well as additional microbiological and toxicological analyses, were performed in the accredited analytical laboratory of the Limited Liability Partnership (LLP) “NPP Ecology of the Future” (Kokshetau, Kazakhstan). The initial material consisted of wastewater from the city of Kokshetau collected at the inlet of municipal wastewater treatment facilities and after mechanical filtration. The studies were conducted in compliance with the European Code of Conduct for Research Integrity [19], the principal framework of scientific ethical standards. Sampling was carried out using Hach Sigma 900 automatic samplers (USA) every 2 hours over a 24-hour period to form an integrated daily composite sample. Samples were transported at 4 °C and analysed within 24 hours.

Wastewater quality parameters before and after preliminary filtration were determined using a set of analytical methods. Suspended solids (mg/L) were assessed gravimetrically after filtration through Whatman GF/C membranes (UK) with drying using Ohaus PR223 balances (USA). Turbidity (NTU) was measured using a Hach 2100N nephelometer (USA). Biochemical oxygen demand BOD₅ (mg O₂/L) was determined using an OxiTop Control WTW system (Germany) after 5-day incubation. Chemical oxygen demand (COD) (mg O₂/L) was measured using a Hach DR3900 photometer (USA) by the dichromate oxidation method. Ammonium (NH₄⁺), nitrates (NO₃⁻), and phosphates (PO₄³⁻) were determined using a Metrohm 881 Compact IC Pro ion chromatograph (Switzerland). Anionic and non-ionic

surfactants (mg/L) were measured spectrophotometrically using a Shimadzu UV-1900 (Japan). Petroleum products (mg/L) were determined using a Horiba OCMA-500 infrared analyser (Japan), while fats and oils were measured gravimetrically after hexane extraction. Total dissolved solids (mg/L) were determined by drying at 180 °C. The volume of coarse sludge (mL/L) was determined using the Imhoff method [20]. Biogas yield potential (m³/kg of removed COD) was calculated based on COD reduction measured using a Hach DR3900 photometer (USA).

Biogas yield and composition under different technological regimes were studied in laboratory-scale Upflow Anaerobic Sludge Blanket (UASB) reactors with a volume of 10 L under mesophilic (35±1 °C) and thermophilic (55±1 °C) conditions. Raw wastewater after mechanical filtration was used as the substrate; anaerobic sludge was pre-acclimatised for 30 days. The methane CH₄ (%) and carbon dioxide CO₂ (%) fractions were determined using an Agilent 7890A gas chromatograph (USA) equipped with a flame ionisation detector (FID) and a thermionic detector (TID). Hydrogen sulphide H₂S (ppm) was measured using Dräger Polytron 8100 electrochemical sensors (Germany). The hydrogen H₂ (%) fraction was determined by gas chromatography using an Agilent 7890A (USA) with a thermal conductivity detector (TCD) and an HP-Molesieve 5A column (USA). Volumetric biogas yield (m³/kg of removed COD) was recorded using a Ritter TG05 gas meter (Germany), while gas production (m³/m³·day) was determined based on the dynamics of gas accumulation in the reactor. The concentration of volatile fatty acids (VFA) (mg/L) was determined by gas chromatography-mass spectrometry (GC-MS) using an Agilent 7890/5977 system (USA). Fermentation pH was measured using a Hach HQ40d electrode (USA), and temperature was controlled by a thermostatic jacket with WIKA sensors (Germany). Biogas density (kg/m³) was calculated based on the gas mixture composition determined chromatographically, using formula (1):

$$\rho_{bg} = \sum_{i=1}^n y_i \rho_i \quad (1)$$

where: ρ_{bg} – the biogas density, kg/m³; y_i – the volumetric fraction of the i -th gas component; ρ_i – the density of the pure component under the given conditions, kg/m³; n – the number of components (CH₄, CO₂, H₂, trace gases).

Gas-phase pressure (kPa) was measured using WIKA sensors. Inhibitory episodes (cases/month) were recorded when a sharp decrease in gas yield occurred, accompanied by an increase in VFA and a drop in pH below 6.5. Membrane post-treatment was performed using an ultrafiltration module made of polysulfone (Koch Membrane Systems, USA) with a nominal pore size of 0.02 μm , operated under cross-flow conditions. Specific permeate flux and transmembrane pressure were recorded at the beginning and end of the filtration cycle, whereas water-quality parameters were determined before and after membrane post-treatment. The specific permeate flux ($\text{L}/\text{m}^2\cdot\text{h}$) was calculated based on the permeate volume and membrane area using formula (2):

$$J = \frac{V}{A \times t} \quad (2)$$

where: J – the specific permeate flux, $\text{L}/\text{m}^2\cdot\text{h}$; A – the membrane area, m^2 ; V – the permeate volume, L ; t – the filtration time, h .

Transmembrane pressure (TMP) (kPa) was recorded using WIKA sensors. The Fouling Index (FI, arbitrary units) was calculated based on the relative decrease in the specific permeate flux using formula (3):

$$FI = \frac{J_0 - J_t}{J_0} \quad (3)$$

where: FI – the fouling index (FI), arbitrary units; J_0 – the initial specific permeate flux, $\text{L}/\text{m}^2\cdot\text{h}$; J_t – the specific permeate flux at time t , $\text{L}/\text{m}^2\cdot\text{h}$.

The rate of deposit accumulation ($\text{mg}/\text{cm}^2\cdot\text{h}$) was determined from the increase in mass of the membrane element dried using Ohaus PR223 balances (USA). The colloidal compaction coefficient (%) was calculated based on the reduction in permeability using formula (4):

$$K_c = \frac{J_0 - J_c}{J_0} \times 100 \quad (4)$$

where: K_c – the colloidal compaction coefficient, %; J_0 – the initial specific permeate flux, $\text{L}/\text{m}^2\cdot\text{h}$; J_c – the flux at critical pressure, $\text{L}/\text{m}^2\cdot\text{h}$.

Residual total organic carbon (TOC) (mg/L) was determined using a Shimadzu TOC-L analyser (Japan), while assimilable organic carbon (AOC) (mg/L) was determined by a bioassay with measurement of residual organic carbon. Residual carbonate hardness (mmol/L) and total alkalinity

TAC ($\text{mg-eq}/\text{L}$) were measured using a Metrohm 848 Titrino Plus titrator (Switzerland) with automatic endpoint detection. Osmotic pressure (kPa) was calculated based on total mineralisation measured with a portable Hach HQ14D conductometer (USA) equipped with an IntelliCAL CDC401 conductivity sensor (USA). The silt density index (SDI) was determined by filtration through a 0.45 μm membrane for 15 minutes. Filtrate pH was monitored using a Hach HQ40d instrument (USA).

Indicators of environmental efficiency included chemical, microbiological, and toxicological parameters recorded before treatment (after mechanical and preliminary filtration) and after complete processing, which made it possible to assess the depth of contaminant reduction at the final stage. Nitrites NO_2^- (mg/L), residual organic nitrogen Org-N (mg/L), and complex phosphates (mg/L) were determined using a Metrohm 881 ion chromatograph (Switzerland). Total heavy metals (mg/L) were measured by inductively coupled plasma optical emission spectrometry (ICP-OES) using a PerkinElmer Optima 8000 (USA). Microplastics (particles/L) were determined by filtration through 0.45 μm membranes and particle counting under a Leica DM500 microscope (Germany). Residual anionic surfactants (A-SAS) and non-ionic surfactants (N-SAS) (mg/L) were recorded spectrophotometrically using a Shimadzu UV-1900 (Japan) based on a two-stage colour reaction. Residual toxicity (% survival) was determined by a 48-hour bioassay using *Daphnia magna* with visualisation under a Leica EZ4 stereomicroscope (Germany). The biodegradability index BOD_5/COD (dimensionless) was calculated from BOD_5 and COD values using formula (5):

$$I_{BD} = \frac{\text{BOD}_5}{\text{COD}} \quad (5)$$

where: I_{BD} – the biodegradability index (BOD_5/COD ratio), dimensionless; BOD_5 – the biochemical oxygen demand over 5 days, $\text{mg O}_2/\text{L}$; COD – the chemical oxygen demand, $\text{mg O}_2/\text{L}$.

The number of *Clostridium* spp. spores (CFU/L) was determined by membrane filtration on selective media (Sigma-Aldrich, USA), followed by incubation in a Binder BD56 thermostat (Germany). The residual mutagenicity index (Ames test, arbitrary units) was calculated based on the number of revertant colonies of *Salmonella typhimurium* strains TA98 and TA100 grown on Oxoid media (United Kingdom), using formula (6):

$$M = \frac{N_{sample}}{N_{control}} \quad (6)$$

where: M – the residual mutagenicity index, arbitrary units; N_{sample} – the number of revertant colonies in the analysed sample; $N_{control}$ – the number of revertant colonies in the negative control.

Residual viral load (adenoviruses, copies/L) was measured by qPCR using an Applied Biosystems 7500 system (USA). Calculation of mean values, standard deviations, and coefficients of variation was performed using Statistica 12.0 software (USA).

RESULTS

Efficiency of pollutant reduction at the pre-filtration stage

One of the indicators demonstrating the highest filtration efficiency is turbidity, the reduction of which reached 64.7%. Such a decrease indicates a high capacity of the filtration system to retain both coarse-dispersed and fine-dispersed inclusions. The big drop in turbidity, which is closely related to the amount of colloidal particles, organo-mineral aggregates, and dissolved flocs, shows that the water's physical and chemical state has stabilised before it goes into the anaerobic reactor. The big drop in suspended solids, which went down by 54.7%, is directly related to the big drop in turbidity. This drop is a strong sign of good performance,

which shows how important preparatory therapy is. By lowering the load on the bioreactor, the chance of dense particles building up and blocking the reactor surface is reduced [21]. The amount of fats and oils was cut by 45.6%, which is a big improvement. Fats and oils are known to cause big difficulties in city sewer systems by producing thick clumps and grease build-ups. The technology was able to separate some hydrophobic fractions, which reduced the fat content by almost half. This reduced the risk of stopping methanogenesis. The strong ability to get rid of fat is linked to a rather small drop in petroleum products (23.8%). This means that the filters are good at soaking up bigger organic molecules but not so good at handling hydrocarbons that are spread out in small amounts.

On the other hand, the dissolved mineral components didn't change much. The drop in nitrates was small, only about 10.8%. This is because nitrate ions are more soluble, which makes it harder for them to stick to the solid particles that mechanical filters usually get rid of. A similar pattern was observed for ammonium, with a decline of 14.3%. This result is expected because the substance is ionic and there isn't much sorption onto the filter parts. The statistics show that first filtration has little effect on the mineral content of the water. This shows that more treatment methods are needed in the next stages of filtering.

In contrast, the potential biogas yield increased by 14.3%. This increase may have resulted from favourable changes in wastewater composition after preliminary filtration, including the partial removal of suspended, hydrophobic, and

Table 1. Parameters of wastewater quality prior to and subsequent to preliminary filtration

Indicator (with units of measurement)	Before filtration	After filtration	Efficiency, %
Suspended solids, mg/L	320	145	54.7
BOD ₅ , mg O ₂ /L	185	128	30.8
COD, mg O ₂ /L	420	295	29.8
Turbidity, NTU	68	24	64.7
Ammonium (NH ₄ ⁺), mg/L	28	24	14.3
Nitrates (NO ₃ ⁻), mg/L	6.5	5.8	10.8
Phosphates (PO ₄ ³⁻), mg/L	3.4	2.5	26.5
Surfactants, mg/L	1.55	1.32	14.8
Petroleum products, mg/L	4.2	3.2	23.8
Fats and oils, mg/L	46	25	45.6
Total solids, mg/L	970	820	15.5
Volume of coarse sludge, mL/L	52	41	21.1
Biogas yield potential, m ³ /kg of removed COD	0.21	0.24	+14.3

Note: compiled by the authors based on All European Academies [19], HACH Company World Headquarters [20].

other substances that could interfere with anaerobic digestion and improved accessibility of the remaining organic fraction to anaerobic microorganisms. This represents a possible explanation for the observed increase rather than a directly confirmed mechanism.

Most measures revealed a general drop, but some changed less dramatically. These changes are nonetheless significant for a full evaluation of the system. For example, phosphates went down by 26.5%, which means that some phosphate ions were taken out, probably by adhering to organic aggregates that the filter caught. The dry residue also dropped by 15.5%, which shows that filtration does work, albeit not as well for dissolved salts and tiny particles (Table 1).

Thus, the analysis of maximum and minimum values confirms that preliminary filtration exerts a pronounced effect primarily on suspended, turbid, and hydrophobic fractions, while having a minimal impact on dissolved mineral and ionic components. High efficiency indicators for turbidity, suspended solids, and fats directly demonstrate the potential of the technology for preparing water for anaerobic digestion, whereas the weak dynamics of ammonium and nitrates indicate the need for subsequent stages to achieve regulatory requirements. The increase in biogas yield potential observed alongside reductions in suspended, hydrophobic, and other contaminant fractions is consistent with the possibility that preliminary treatment creates more favourable conditions for anaerobic digestion; however, this mechanism was not directly confirmed in the present study.

Gas generation parameters under mesophilic and thermophilic conditions

One of the indicators exhibiting the highest values was gas production, which under mesophilic conditions amounted to 0.75–0.92 m³ of biogas per 1 m³ of reactor volume per day, whereas under thermophilic conditions it reached 1.05–1.18 m³/m³·day. The lower and upper limits reflected changes in gas generation intensity during the transition from a moderate temperature range to higher temperatures. Gas production values under thermophilic conditions were consistently higher than the corresponding mesophilic values, indicating the temperature dependence of the rate of organic matter degradation. Since biogas volume represented the outcome of the combined processes of hydrolysis, acetogenesis, and

methanogenesis, differences between the regimes reflected varying degrees of completion of these stages under the given conditions.

The secondary cluster of elevated values was associated with the methane (CH₄) component. Under mesophilic conditions, methane concentrations ranged from 58% to 64%, and under thermophilic conditions, they elevated to between 66% and 71%. These readings represented some of the highest concentrations recorded for any components in the gas combination. The variation in these values reflects the ongoing changes in the biogas composition, while the difference between the two temperature regimes highlights shifts in the balance of methanogenic processes. The increased methane concentration at rising temperatures was associated with the varying speeds at which methanogenic bacteria metabolise acetate and hydrogen. This range of values included both stable and more dynamic phases of methanogenesis, rendering methane concentration an essential measure for comparing various temperature settings. Conversely, the lowest values were seen for hydrogen (H₂) concentration. Under mesophilic conditions, hydrogen concentration varied from 0.4 to 0.7%, while under thermophilic conditions it varied from 0.2 to 0.4%. These levels were the most minimal among all gas components included in the table. The data indicated transitional processes between the acetogenic and methanogenic phases, as hydrogen served as an intermediate product and was swiftly utilised by hydrogenotrophic methanogens. The limited range demonstrated a pronounced sensitivity of hydrogen concentration to variations in reaction kinetics and its reliance on the pace of subsequent conversion to methane. As thermophilic conditions were established, the minimum values decreased further, indicating an altered reaction equilibrium at higher temperatures.

Among the indicators exhibiting low values was also hydrogen sulphide (H₂S) concentration. Under mesophilic conditions, it ranged from 150 to 180 ppm, while under thermophilic conditions it ranged from 110 to 150 ppm. The absolute values of hydrogen sulphide were higher than those of hydrogen but remained significantly lower than those of components such as methane and carbon dioxide. The range reflected the residual content of sulphur-containing compounds in the substrate and their transformation under anaerobic conditions. The relatively narrow interval placed this

indicator among those with minimal absolute representation in the gas mixture.

The group of high values also included the concentration of volatile fatty acids (VFA). Under mesophilic conditions, VFA levels ranged from 320 to 410 mg/L, whereas under thermophilic conditions they ranged from 420 to 510 mg/L. These values were among the highest chemical parameters of the process and reflected the level of intermediate products of hydrolysis and fermentation. The range demonstrated the pattern of organic acid accumulation at different stages of substrate biodegradation. The difference between the regimes indicated changes in the rates of hydrolytic and acetogenic processes. Although VFAs were not components of the final gas, they determined the conditions of subsequent stages and served as a sensitive indicator of potential changes in process performance. Gas-phase pressure also belonged to the category of high values. Under mesophilic conditions, it ranged from 6.2 to 7.1 kPa, whereas under thermophilic conditions it ranged from 7.4 to 8.3 kPa. These values were among the upper range of all parameters presented in the table. Pressure reflected the cumulative accumulation of gases in the reactor and characterised the degree of gas-phase saturation. The range remained stable within each regime but demonstrated a clear shift towards higher values at elevated temperature. For comparison of parameters exhibiting opposite trends between regimes, the carbon dioxide (CO₂) fraction was used. Under mesophilic conditions, values ranged from 33 to 38%, whereas under thermophilic conditions they ranged from 27 to 32%. This parameter belonged to the group

with high absolute values but demonstrated a tendency to decrease with increasing temperature, distinguishing it from the dynamics of methane. The range reflected changes in CO₂ proportion resulting from differences in the completeness of methanogenic reactions (Table 2).

Thus, among all numerical data, indicators with either the highest or the lowest values were identified: gas production, methane concentration, volatile fatty acid concentration, and gas-phase pressure – as the principal parameters with high values; hydrogen and hydrogen sulphide concentrations – as indicators with minimal values; and carbon dioxide concentration – as a parameter with high values but dynamics opposite to those of methane. These groups formed the basis for analysing differences between mesophilic and thermophilic anaerobic digestion regimes.

Dynamics of filtration processes on the membrane module

One of the parameters exhibiting the highest absolute values was transmembrane pressure (TMP). At the beginning of the filtration cycle, TMP values were in the range of 45–55 kPa, increasing to 72–88 kPa by the end of the cycle. The recorded change reflected an increase in hydraulic resistance of the filtering surface arising from the accumulation of colloidal particles, organic compounds, and coagulation products present in the influent water on the membrane. As the resistance progressively raised, the lower and upper TMP limits slowly moved, showing that the membrane's permeability changed while it was in use. The TMP dynamics showed that the pressure didn't rise evenly. At the

Table 2. Biogas yield and composition parameters under different technological regimes

Indicator (units of measurement)	Mesophilic regime	Thermophilic regime
Methane fraction (CH ₄), %	58–64	66–71
Carbon dioxide fraction (CO ₂), %	33–38	27–32
Hydrogen sulphide (H ₂ S), ppm	150–180	110–150
Hydrogen (H ₂), %	0.4–0.7	0.2–0.4
Biogas yield, m ³ /kg of removed COD	0.28–0.32	0.31–0.36
Gas production rate, m ³ /m ³ of reactor·day	0.75–0.92	1.05–1.18
Volatile fatty acid (VFA) concentration, mg/L	320–410	420–510
Fermentation pH	6.8–7.1	7.2–7.4
Temperature, °C	35–38	50–55
Biogas density, kg/m ³	1.12–1.15	1.15–1.18
Gas-phase pressure, kPa	6.2–7.1	7.4–8.3
Inhibitory episodes, cases/month	2–3	1–2

start of the cycle, the values stayed close to the lower limits and then rose as a fouling layer formed. This made it possible to interpret TMP as one of the principal parameters structurally and functionally reflecting the state of the membrane unit, since it was the most sensitive to the combined influence of all types of contaminants retained on the surface.

The second group of high absolute values comprised osmotic pressure, which determined the total content of dissolved salts and low-molecular-weight ions in the water. Before membrane treatment, osmotic pressure ranged from 240 to 250 kPa, whereas after filtration it ranged from 220 to 230 kPa. Despite the decrease, the absolute level remained among the highest of all parameters considered. Changes in osmotic pressure reflected redistribution of the mineral fraction, as the membrane allowed most salts to pass while retaining complex organo-mineral structures. Thus, this parameter reflected not purification as such, but changes in the structure of the dissolved phase under conditions of mechanical-selective separation of water and impurities. The drop in osmotic pressure showed that the balance between dissolved salts and eliminated high-molecular-weight complexes had changed, which was a sign of mineral composition redistribution.

The silt density index (SDI), which shows how likely water is to induce membrane fouling, has one of the most noticeable and least noticeable final values. Before the membrane stage, the SDI

was between 6.5 and 7.2 units. After filtration, it dropped to between 1.2 and 1.6 units. This range was one of the most important adjustments in relation to all the other parameters. SDI defined the density of fine-dispersed particles that were not captured during the mechanical phase but might infiltrate membrane pores. The drop in its value was due to a drop in the number of particles that were around 0.5 μm or smaller. The small readings after the membrane stage showed that this impurity fraction had been greatly reduced. This was shown by both the range getting smaller and the values getting near to the lower detectable limit.

In contrast to SDI, but also belonging to the group of minimal values, the parameter with the lowest concentrations was AOC. Prior to the membrane stage, its level ranged from 2.8 to 3.4 mg/L, whereas after treatment it ranged from 0.4 to 0.6 mg/L. These values were among the lowest of all organic parameters presented in the table. AOC reflected the concentration of low-molecular-weight organic substances capable of serving as substrates for microbial growth. The decrease in AOC level indicated retention of such compounds and reduction of their concentration in the filtrate. The post-treatment range demonstrated low variability and belonged to the group of minimal values, reflecting structural transformation of the dissolved organic fraction.

A parameter also associated with low final values was residual total organic carbon (TOC).

Table 3. Performance characteristics of the ultrafiltration membrane stage

Indicator (units of measurement)	Initial value	Final value
Specific permeate flux, $\text{L}/\text{m}^2\cdot\text{h}$	85–92	58–63
Transmembrane pressure (TMP), kPa	45–55	72–88
Fouling Index (FI), arbitrary units	–	16–22
Silt density index (SDI)	6.5–7.2	1.2–1.6
Rate of deposit accumulation on the membrane, $\text{mg}/\text{cm}^2\cdot\text{h}$	–	0.45–0.62
Colloidal compaction coefficient, %	–	28–35
Residual total organic carbon (TOC), mg/L	22–28	4–6
Adsorbable organic matter (AOC), mg/L	2.8–3.4	0.4–0.6
Residual carbonate hardness, mmol/L	3.6	2.8–3.1
Alkalinity (TAC), mg-eq/L	4.2	3.5–3.7
Osmotic pressure, kPa	240–250	220–230

Note: For specific permeate flux and TMP, the initial and final values correspond to the beginning and end of the filtration cycle, respectively; for water-quality indicators, they correspond to measurements before and after membrane post-treatment. Thus, among all membrane treatment indicators, the highest values were demonstrated by transmembrane pressure, osmotic pressure, and specific permeate flux; the lowest values were observed for adsorbable organic matter, residual organic carbon, the silt density index (SDI), and the rate of deposit formation. These parameters formed the basis for analysing the processes occurring at different stages of membrane treatment and reflected differences between the hydraulic, organic, and dispersed characteristics of the treated water.

Prior to the membrane stage, its concentration was 22–28 mg/L, decreasing to 4–6 mg/L after treatment. TOC characterised the total mass of dissolved organic substances, and its reduction reflected the extent of removal of all groups of organic molecules whose size exceeded the membrane pore range. Low TOC values after treatment indicated an improvement in water quality with respect to dissolved organic content. At the same time, a parameter reflecting the rate of deposit accumulation on the membrane was recorded, amounting to 0.45–0.62 mg/cm²·h. This indicator belonged to the group of low values but was of key importance for analysing membrane fouling. It demonstrated the initial rate of fouling layer formation on the membrane, allowing it to be interpreted as a functional marker of the transition of the membrane from a state of high permeability to one of increased resistance. The specific permeate flux decreased from 85–92 L/m²·h at the beginning of the filtration cycle to 58–63 L/m²·h at the end of the cycle. This parameter combined features of high and decreasing values, since its absolute levels remained relatively high while the dynamics indicated a reduction in membrane permeability as a result of fouling layer formation (Table 3).

Environmental quality and treatment stability indices

Nitrite (NO₂⁻) concentration was among the indicators that demonstrated the lowest final level after complete wastewater treatment. Initial values were approximately 2.1 mg/L, corresponding to the range typical of urban wastewater with active nitrification processes. After the biological phase, membrane separation, and stabilisation of the nitrogenous portion, the quantities dropped to about 0.08 mg/L. This decrease showed that the formation of intermediate nitrite had stopped and that nitrogen molecules were changing into more stable forms. The low values that stayed between 0.08 and 0.12 mg/L showed that the membrane barrier was able to keep both nitrifying cells and suspended particles that might be used as substrates for nitrite production. This confirmed the completion of biological activity and the stability of the nitrogen balance.

A similar trend was observed for residual organic nitrogen (Org-N), a key component of the organic fraction of wastewater. Before treatment, the level reached 34 mg/L, which means that there were high-molecular-weight structures present,

like protein molecules, biomass breakdown products, and humic-like complexes. After all of the treatment phases were finished, the concentrations fell to 7–11 mg/L. This change showed that big organic molecules were breaking down during anaerobic digestion and that the membrane filter was getting rid of colloidal forms. The low final values indicated that the filtering barrier either eliminated or conserved most of the nitrogen-containing organic components, which made them less important for the environment in the treated water.

A substantial relative change was also observed for microplastic content. In the influent water, concentrations reached up to 2400 particles/L, which is characteristic of urban wastewater containing synthetic fibres, abrasive detergent particles, and fragments of household plastics. After membrane post-treatment, concentrations decreased to approximately 110 particles/L. A reduction by more than an order of magnitude indicated the ability of membranes to retain particles smaller than 200 µm, including fragments that may not be removed by conventional methods. The range of 110–180 particles/L reflected minimal residual quantities. This reduction decreased the likelihood of transport of pollutants sorbed onto microplastics – such as surfactants, pharmaceutical compounds, and heavy metals – that are capable of migrating into natural water bodies.

Changes were also observed in residual toxicity, determined based on the survival of *Daphnia magna*. Prior to treatment, survival remained at approximately 35%, reflecting the impact of a complex of toxicants, including poorly oxidisable organic substances, surfactants, and micro-pollutants. After the membrane stage, survival increased to the range of 82–91%. This increase indicated a reduction in overall toxic impact and decreased concentrations of substances capable of inhibiting the vital functions of test organisms. This parameter reflected the integrated effect of the entire treatment process, as bioassays respond to the combined presence of contaminants rather than to individual substances.

Changes in the structure of the organic fraction were clearly reflected in the dynamics of the biodegradability index BOD₅/COD. The initial index was approximately 0.18, indicating the predominance of poorly oxidisable organic compounds in the influent wastewater. After all of the treatment phases were finished, the indicator almost doubled, going from 0.39 to 0.47. This meant that the membrane filter was able

Table 4. Comprehensive assessment of biological and chemical impacts

Indicator (units of measurement)	Before treatment	After complete treatment
Nitrites (NO_2^-), mg/L	1.6–2.1	0.08–0.12
Residual organic nitrogen (Org-N), mg/L	28–34	7–11
Complex phosphates, mg/L	3.2–4.0	0.9–1.4
Total heavy metals, mg/L	0.28–0.35	0.05–0.08
Microplastics, particles/L	1800–2400	110–180
Residual anionic surfactants (A-SAS), mg/L	1.10–1.45	0.12–0.18
Residual non-ionic surfactants (N-SAS), mg/L	0.85–1.20	0.09–0.14
Residual toxicity (<i>Daphnia magna</i>), % survival	35–48	82–91
Biodegradability index BOD_5/COD , dimensionless	0.18–0.24	0.39–0.47
Number of <i>Clostridium</i> spp. spores, CFU/L	1.1×10^4	$<10^2$
Residual viral load (adenoviruses), copies/L	10^4 – 10^5	$<5 \times 10^1$
Residual mutagenicity index (Ames test), arbitrary units	1.8–2.4	0.4–0.6

to eliminate or keep less persistent high-molecular-weight organic compounds. The rise in the biodegradability index showed that the structure of the residual organic load became more accessible and could be oxidised further. So, variations in the index showed that the organic part of the water changed in both quantity and quality.

The adenoviruses residual viral load indicator was recorded before and after the whole wastewater treatment. Before treatment, the concentrations were about 10^5 copies/L, which is typical of levels found in municipal wastewater. After going through the membrane barrier, the leftover concentrations dropped to about 5×10^1 copies/L. This was one of the biggest drops in all of the microbiological indicators. Minimal levels showed that membrane separation can hold onto virus particles that are about the same size as the membrane pore size. The decrease may have occurred due to the partial destruction of viral structures in anaerobic environments, the elimination of cellular carriers, and mechanical retention on the membrane surface (Table 4).

The analysis of the selected indicators revealed that the most significant changes occurred in areas related to the reduction of nitrite, organic nitrogen, microplastics, and viral load concentrations. The levels went down to about the minimum for treated water. Nitrites, which were once associated to active nitrogen transformation, were brought down to levels that were not significant. There was a big drop in organic nitrogen, which means that long-lasting organic materials were breaking down. Microplastics saw a decrease of more than ten times, showing that even tiny, scattered particles were kept in good condition. In the

end, the viral load dropped by several orders of magnitude, which means that almost all of the viral particles were killed.

DISCUSSION

The results clearly show that the many stages of technology, starting with preliminary filtration, work to different degrees. The turbidity went down by 64.7%, while the suspended solids went down by 54.7%. These results highlight the critical role of mechanical filtration as a fundamental process that ensures the stability of subsequent treatment phases. This reduction represents a substantial drop in the dispersed load and reduces the likelihood of mechanical siltation in the anaerobic reactor. A similar pattern was observed with fats and oils, which decreased by 45.6%, hence reducing the probability of obstructing methanogenesis and preventing the formation of dense lipid clusters. Nitrates and ammonium showed almost no change, with just 10.8% and 14.3% drops, respectively. This shows that mechanical filtering is not very effective in getting rid of dissolved mineral compounds. This shows that we need more biological or membrane-based methods to deal with these toxins [22]. Lastly, the findings of the biogas fermentation showed that temperature had a clear effect. The higher VFA concentration under thermophilic conditions (420–510 mg/L compared with 320–410 mg/L under mesophilic conditions) may reflect faster hydrolysis and acidogenesis relative to subsequent VFA consumption, resulting in greater accumulation of intermediate organic acids. At the same time, maintaining the

thermophilic regime at approximately 55 °C rather than the mesophilic regime at approximately 35 °C would be expected to require greater heat input; therefore, the higher gas production observed under thermophilic conditions should be considered together with the potentially greater energy demand of this regime.

Quantitatively, the thermophilic methane fraction obtained in the present study (66–71%) exceeded the 58.05% CH₄ reported by Ningsih et al. [23] during acclimatisation of an anaerobic baffled reactor treating tofu wastewater, while the mesophilic range (58–64%) was broadly comparable. For membrane operation, the specific permeate flux recorded in the present study (85–92 L/m²·h initially and 58–63 L/m²·h at the end of the cycle) was higher than the 15–25 L/m²·h 20 °C-standardised flux reported by Jiménez-Benítez et al. [24] for a semi-industrial AnMBR treating urban wastewater. These comparisons should be interpreted cautiously because the studies used different wastewater substrates, reactor configurations, operating temperatures, and membrane arrangements.

In the context of studies on semi-industrial membrane systems, Jiménez-Benítez et al. [24] and C. Wang et al. [25] analysed primarily the energy and gas-related performance indicators of installations designed for the treatment of municipal and high-strength wastewater. In the study by Jiménez-Benítez et al., it was shown that primary attention was devoted to the balance of energy consumption of the anaerobic membrane bioreactor (AnMBR) system and greenhouse gas emissions, whereas the preliminary filtration block and the detailed dynamics of turbidity, suspended solids, and fats were scarcely described. In the study by C. Wang et al., the main focus was the assessment of methane yield and the energy feasibility of biomethane production, while membrane post-treatment indicators and a comprehensive analysis of the quality of influent and treated wastewater were absent. In contrast to these works, the present study links reductions in turbidity by 64.7%, suspended solids by 54.7%, and fats by 45.6% with a subsequent increase in gas production to 1.05–1.18 m³/m³·day, an increase in the CH₄ fraction to 66–71%, and an increase in biogas yield potential by 14.3%, which makes it possible to trace a direct technological chain of “filtration – fermentation – environmental effect”.

Within methodological approaches to wastewater treatment plant configuration, Tsui et al. [26] and Bermúdez et al. [27] mainly considered

infrastructure development scenarios and opportunities for water reuse. In the study by Tsui et al., it was shown that technology selection prioritised economic trade-offs and cost structures, while actual changes in specific effluent quality indicators (turbidity, suspended solids, fats, petroleum products) and biogas fermentation parameters remained outside the focus. In the work by Bermúdez et al., primary attention was paid to the suitability of membrane-treated effluents for agricultural irrigation and compliance with sanitary standards; however, the absence of analysis of biogas composition, methane fraction, and VFA dynamics limited insight into anaerobic unit performance. Together, these studies highlight the importance of considering treatment configuration and effluent quality when evaluating integrated wastewater systems.

Within the framework of resource-oriented wastewater management, Ulusoy et al. [28] and Rey-Martínez et al. [29] emphasised strategic approaches to sustainable use of water and nutrient resources. In the work by Ulusoy et al., the importance of innovative management schemes was highlighted; however, the analysis remained at a conceptual level without reference to dispersed water quality indicators, gas-phase characteristics, or the influence of preliminary filtration on the risk of methanogenesis inhibition. In the review by Rey-Martínez et al., combinations of technologies for nitrogen and phosphorus recovery were systematised, but issues related to changes in turbidity, suspended solids, fats, gas production, and environmental indices of the final effluent were addressed fragmentarily. These resource-oriented perspectives emphasise the need to assess treatment performance together with water and nutrient recovery.

In studies focused on the conversion of wastewater into intermediate biodegradation products, the works of Castro-Fernandez et al. [30] and Porto et al. [31] demonstrated broad coverage of technological approaches. In the study by Castro-Fernandez et al., the production of volatile fatty acids (VFA) from a mixture of activated sludge and food waste with subsequent environmental assessment was examined; however, preliminary filtration parameters were not included among the factors influencing fermentation kinetics. In the work by Porto et al., a bibliometric analysis of biogas utilisation over five decades was conducted, focusing on energy trends without considering changes in influent water quality and their influence on methane

yield. These findings underscore the relevance of substrate composition and pretreatment conditions to subsequent fermentation behaviour [32–34].

In the context of studies aimed at improving methanogenesis efficiency, the research by Kazimierowicz et al. [35] and Ningsih et al. [23] constituted important methodological developments but exhibited notable limitations. In the work by Kazimierowicz et al., primary attention was paid to biogas upgrading and chemical preparation of the substrate; however, mechanical wastewater quality parameters – suspended solids, fats, petroleum products – were not considered as factors influencing methanogenesis stability. Ningsih et al. described acclimatisation of the anaerobic process during treatment of soybean-processing wastewater, but the study did not include assessment of changes in water composition prior to fermentation and lacked comparison with preliminary treatment stages. In the present study, removal of coarse and fine dispersed particles and reductions in turbidity, lipid fractions, and petroleum products were accompanied by increased gas production potential, which may indicate more favourable conditions for anaerobic digestion rather than a directly confirmed causal mechanism.

In studies related to membrane technologies for urban treatment systems, the works of Bermúdez et al. [36] and Capodaglio [37] analysed the potential for wastewater reuse. In the study by Bermúdez et al., primary attention was devoted to membrane bioreactors (MBR) and permeate quality for subsequent agricultural application; however, total organic carbon (TOC), AOC, silt density index (SDI), and transmembrane pressure (TMP) were considered without comparison to preliminary filtration. In the work by Capodaglio, approaches to resource recovery from urban wastewater were analysed, but without a detailed link to the characteristics of mechanical water preparation. The combined evidence indicates that membrane performance should be interpreted together with upstream wastewater preparation [38–40].

In the field of bioconversion of organic substrates, the works of Alengebawy et al. [41] and Garkoti and Thengane [42] examined the potential of biogas technologies within the context of circular solutions. In the study by Alengebawy et al., attention was focused on the processing of agricultural waste with emphasis on anaerobic degradation regimes; however, the dynamics of turbidity, suspended solids, and lipid fractions prior to fermentation were not analysed. In the work

by Garkoti and Thengane, a techno-economic assessment of various biogas plant configurations was performed, but the influence of preliminary removal of dispersed inclusions on gas generation and reactor operational stability was not considered. The observed reductions in turbidity and fats may therefore be relevant to subsequent gas-production dynamics, although the mechanism was not directly tested.

In the domain of technological advancement in treatment processes, the research conducted by Silva [43] and Rodrigues et al. [44] focused on the increase of the capabilities of water treatment and energy systems. The research conducted by Silva investigated the potential for the reuse of treated water; however, the alterations in physico-chemical properties during the filtration process—specifically the decreases in turbidity, suspended solids, and fats—were not correlated with the subsequent biochemical behaviour of the substrate within the reactor. Rodrigues and others put together information on biogas production technology from all over the world. However, they didn't compare gas mixture metrics, like how methane, carbon dioxide, or hydrogen sulphide move about under different conditions, with the quality of the influent after mechanical processing [45]. In the present data, reductions in lipid and petroleum fractions occurred alongside lower H₂S concentrations and a higher methane fraction; no statistical correlation analysis was reported.

In the context of substrate quality evaluation and resource solution analysis, the studies conducted by Wani and Parveez [46] and Rathore et al. [47] investigated the potential for sludge utilisation and compared scenarios of technological systems. The research conducted by Wani and Parveez examined the qualities of sludge for energy applications; however, initial reductions in suspended particles, lipid agglomerates, and petroleum products were not included in the analysis of substrate stability. Rathore et al. did a life-cycle assessment of technologies, but they didn't compare changes in chemical flow parameters like nitrate, ammonium, phosphate, and organic matter concentrations with the effects of mechanical filtration and how it affects fermentation and membrane stages. Overall, the reductions in nitrites, organic nitrogen, and microplastics occurred alongside increased *Daphnia magna* survival and a higher BOD₅/COD index, indicating improved environmental characteristics of the treated water across the integrated treatment sequence.

CONCLUSIONS

The conducted study provided a comprehensive assessment of the effectiveness of three key stages of wastewater treatment: preliminary filtration, anaerobic fermentation, and membrane post-treatment. The influent wastewater was characterised by high levels of suspended solids (320 mg/L), chemical oxygen demand (COD) (420 mg O₂/L), biochemical oxygen demand (BOD₅) (185 mg O₂/L), turbidity (68 NTU), fats (46 mg/L), and petroleum products (4.2 mg/L). After mechanical filtration, concentrations decreased by 14–65%, including reductions in suspended solids to 145 mg/L (-54.7%), turbidity to 24 NTU (-64.7%), and fats to 25 mg/L (-45.6%), while biogas formation potential increased from 0.21 to 0.24 m³/kg of removed COD (+14.3%). Comparison of mesophilic and thermophilic anaerobic fermentation regimes demonstrated the advantage of the high-temperature process. Under thermophilic conditions, the methane (CH₄) fraction reached 66–71%, compared with 58–64% under mesophilic conditions, and gas production increased from 0.75–0.92 to 1.05–1.18 m³/m³·day. At the same time, the CO₂ fraction decreased (from 33–38% to 27–32%) and hydrogen sulphide (H₂S) concentration was reduced (150–180 → 110–150 ppm), which improved biogas quality. A reduction in the number of inhibitory episodes was also observed (1–2 versus 2–3 cases/month), and pH was more stable (7.2–7.4 versus 6.8–7.1). Membrane post-treatment ensured a substantial reduction in residual contaminants. Total organic carbon (TOC) decreased from 22–28 to 4–6 mg/L, while assimilable organic carbon (AOC) was reduced from 2.8–3.4 to 0.4–0.6 mg/L. The silt density index (SDI) decreased from 6.5–7.2 to 1.2–1.6 units, indicating increased filtrate stability. Environmental assessment confirmed the depth of post-treatment: nitrite levels decreased from 1.6–2.1 to 0.08–0.12 mg/L, residual organic nitrogen from 28–34 to 7–11 mg/L, heavy metals from 0.28–0.35 to 0.05–0.08 mg/L, and microplastics from 1.800–2.400 to 110–180 particles/L. *Daphnia magna* survival increased from 35–48% to 82–91%, the biodegradability index BOD₅/COD increased from 0.18–0.24 to 0.39–0.47, and viral load decreased to <5 × 10¹ copies/L. The limitation of the study is associated with the analysis of a single type of wastewater and fixed treatment regimes. Further research should encompass other substrates and variable technological conditions.

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REFERENCES

1. Lyubchik, S., Lygina, E., Lyubchik, A., Lyubchik, S., Loureiro, J.M., Fonseca, I.M., Ribeiro, A.B., Pinto, M.M., Figueiredo, A.M.S. (2015). The kinetic parameters evaluation for the adsorption processes at “liquid-solid” interface. *Electrokinetics Across Disciplines and Continents: New Strategies for Sustainable Development*, 81–109. https://doi.org/10.1007/978-3-319-20179-5_5
2. Trus, I., Gomelya, N., Halysh, V., Radovenchyk, I., Stepova, O., Levytska, O. (2020). Technology of the comprehensive desalination of wastewater from mines. *Eastern-European Journal of Enterprise Technologies*, 3(6–105), 21–27. <https://doi.org/10.15587/1729-4061.2020.206443>
3. Bilan, Y., Zos-Kior, M., Nitsenko, V., Sinelnikau, U., Ilin, V. (2017). Social component in sustainable management of land resources. *Journal of Security and Sustainability Issues*, 7(2), 107–120. [https://doi.org/10.9770/jssi.2017.7.2\(9\)](https://doi.org/10.9770/jssi.2017.7.2(9))
4. Kaipova Z., Satayev M., Turgyn D., Ibraimova Z., Latif A. (2024). Modern status of technology for production of highly concentrated methane by biogas purification. *EVERGREEN*, 11(4), 2969–2982. <https://doi.org/10.5109/7326938>
5. Bayazitova Z., Kurmanbayeva A., Kakabayev A., Belgibayeva A., Baidalin M., Bogapov I. (2023). Impacts of anaerobic thermophilic fermentation on physicochemical characteristics of effluents derived from diverse organic feedstocks. *International Journal of Design & Nature and Ecodynamics*, 18(6), 1417–1425. <https://doi.org/10.18280/ij dne.180615>
6. Kominko H., Gorazda K., Wzorek Z. (2017). The possibility of organo-mineral fertilizer production from sewage sludge. *Waste and Biomass Valorization*, 8(5), 1781–1791. <https://doi.org/10.1007/s12649-016-9805-9>
7. Abilmazhinov E.T., Akimzhanov A.Zh., Shaiakhmetov E.Y., Anibaev S.N., Nurgaliyev N.N., Shakerkhan K.O., Sailauov D.M. (2021). Development of the biogas industry and prospects for the implementation of biogas plants in Kazakhstan. *Eurasian Physical Technical Journal*, 18(3(37)), 76–82. <https://phtj.buketov.edu.kz/index.php/EPTJ/article/download/115/91/924>

8. Yerassyl D., Jin Y., Zhanar S., Aigul K., Saltanat Y. (2022). The current status and lost biogas production potential of Kazakhstan from anaerobic digestion of livestock and poultry manure. *Energies*, 15(9), 3270. <https://doi.org/10.3390/en15093270>
9. Amirkhanov B., Kunelbayev M., Issa S., Amirkhanova G., Nurgazy T., Zhumasheva A., Alipbeki O. (2025). Enhancing sustainable biogas generation through a real-time digital twin of a modular bioreactor. *Journal of Applied Data Sciences*, 6(4), 2312–2331. <https://doi.org/10.47738/jads.v6i4.779>
10. Freitas F.F., Coelho U.R., Silva S.T.S., Gomes A.A.L., Barros R.M., Filho G.L.T., Lora E.E.S., dos Santos I.F.S. (2022). Study of the potential for energy use of biogas from a wastewater treatment plant to a medium-sized city: A technical, economic and environmental analysis. *Waste and Biomass Valorization*, 13(8), 3509–3521. <https://doi.org/10.1007/s12649-022-01727-8>
11. Un C. (2025). Assessing biogas from wastewater treatment plants for sustainable transportation fuel: A detailed analysis of energy potential and emission reductions. *Gases*, 5(1), 6. <https://doi.org/10.3390/gases5010006>
12. Ciula J., Kowalski S., Wiewiórska I. (2023). Pollution indicator of a megawatt hour produced in cogeneration-the efficiency of biogas purification process as an energy source for wastewater treatment plants. *Journal of Ecological Engineering*, 24(3), 232–245. <http://dx.doi.org/10.12911/22998993/158562>
13. Werkneh A.A. (2022). Biogas impurities: environmental and health implications, removal technologies and future perspectives. *Heliyon*, 8(10), e10929. <https://doi.org/10.1016/j.heliyon.2022.e10929>
14. Nematov, D.D., Burhonzoda, A.S., Kholmurodov, K.T., Lyubchik, A.I., Lyubchik, S.I. (2023). A detailed comparative analysis of the structural stability and electron-phonon properties of ZrO₂: Mechanisms of water adsorption on t-ZrO₂ (101) and t-YSZ (101) surfaces. *Nanomaterials*, 13(19), 2657. <https://doi.org/10.3390/nano13192657>
15. Shumka, S., Kalogianni, E., Šanda, R., Vukić, J., Shumka, L., Zimmerman, B. (2020). Ecological particularities of the critically endangered killifish Valencia letourneuxi and its spring-fed habitats: A long-lost endemic species of south Albania. *Knowledge and Management of Aquatic Ecosystems*, 2020(421), 45. <https://doi.org/10.1051/kmae/2020036>
16. Lyubchik, S.B., Perepichka, I.I., Galushko, O.L., Lyubchik, A.I., Lygina, E.S., Fonseca, I.M. (2005). Optimization of the conditions for the Cr (III) adsorption on activated carbon. *Adsorption*, 11(5-6), 581–593. <https://doi.org/10.1007/s10450-005-5616-1>
17. Miyawaki B., Mariano A.B., Vargas J.V.C., Balmant W., Defrancheschi A.C., Corrêa D.O., Santos B., Selesu N.F.H., Ordonez J.C., Kava V.M. (2021). Microalgae derived biomass and bioenergy production enhancement through biogas purification and wastewater treatment. *Renewable Energy*, 163, 1153–1165. <https://doi.org/10.1016/j.renene.2020.09.045>
18. Castellanos-Sánchez J.E., Aguilar-Aguilar F.A., Hernández-Altamirano R., Venegas J.A.V., Aryal D.R. (2024). Biogas purification processes: review and prospects. *Biofuels*, 15(2), 215–227. <https://doi.org/10.1080/17597269.2023.2223801>
19. All European Academies. (2023). *The European Code of Conduct for Research Integrity: 2023 revised edition*. <http://www.doi.org/10.26356/ECOC>
20. HACH Company World Headquarters. (2015). *Solids, settleable matter*. <https://cdn.hach.com/7FYZVWYB/at/5ng3kn338f9vv4f3v5rrthg/DOC3165301202.pdf>
21. Kulikova, D. (2021). Justifying the expediency in modernizing constructions for fatcontaining wastewater treatment: a case study of the vegetable oils producing factory LLC “Potoky”. *Ecological Safety and Balanced Use of Resources*, 12(2), 102–111. [https://doi.org/10.31471/2415-3184-2021-2\(24\)-102-111](https://doi.org/10.31471/2415-3184-2021-2(24)-102-111)
22. Akhkozov, L., Gorban, O., Danilenko, I., Gorban, S., Volkova, G., Bryukhanova, I., Shapovalova, O., Lyubchik, S., Konstantinova, T. (2020). Optical properties, photocatalytic and bactericide activity of pure and Ag-decorated Zr, al-doped ZnO. *NANO-CON Conference Proceedings - International Conference on Nanomaterials, 2020*, 186–192. <https://doi.org/10.37904/nanocon.2019.8535>
23. Ningsih L.M., Hasanudin U., Roubik H. (2024). Acclimatisation process of biogas production from tofu industrial wastewater using biofilter in anaerobic baffled reactor (ABR). *Renewable Energy*, 236, 121519. <https://doi.org/10.1016/j.renene.2024.121519>
24. Jiménez-Benítez A., Ruiz-Martínez A., Robles Á., Serralta J., Ribes J., Rogalla F., Seco A., Ferrer J. (2023). A semi-industrial AnMBR plant for urban wastewater treatment at ambient temperature: Analysis of the filtration process, energy balance and quantification of GHG emissions. *Journal of Environmental Chemical Engineering*, 11(2), 109454. <https://doi.org/10.1016/j.jece.2023.109454>
25. Wang C., Li Z., Tan R.R., Aviso K.B., Wang F., Jia X. (2024). Feasibility analysis for bio-natural gas generated from high-concentration organic wastewater. *Energy*, 313, 133708. <https://doi.org/10.1016/j.energy.2024.133708>
26. Tsui T.-H., Zhang L., Zhang J., Dai Y., Tong Y.W. (2022). Methodological framework for wastewater treatment plants delivering expanded service: Economic tradeoffs and technological decisions. *Science of the Total Environment*, 823, 153616. <https://doi.org/10.1016/j.scitotenv.2022.153616>
27. Bermúdez L.A., Díaz J.C.L., Pascual J.M., Martínez M.D.M.M., Capilla J.M.P. (2022). Study of the potential for agricultural reuse of urban wastewater with membrane bioreactor technology in the circular economy framework. *Agronomy*, 12(8), 1877. <https://doi.org/10.3390/agronomy12081877>

28. Ulusoy A., Atılğan A., Rolbiecki R., Jagosz B., Rolbiecki S. (2024). Innovative approaches for sustainable wastewater resource management. *Agriculture*, 14(12), 2111. <https://doi.org/10.3390/agriculture14122111>
29. Rey-Martínez N., Torres-Sallan G., Morales N., Serra E., Bisschops I., van Eekert M.H.A., Borràs E., Sanchis S. (2024). Combination of technologies for nutrient recovery from wastewater: A review. *Cleaner Waste Systems*, 7, 100139. <https://doi.org/10.1016/j.clwas.2024.100139>
30. Castro-Fernandez A., Estévez S., Lema J.M., Taboada-Santos A., Feijoo G., Moreira M.T. (2025). Large-scale commercial-grade volatile fatty acids production from sewage sludge and food waste: A holistic environmental assessment. *Environmental Science and Ecotechnology*, 23, 100518. <https://doi.org/10.1016/j.ese.2024.100518>
31. Porto P.M.B.V., de Oliveira Anício S., Vasconcelos R.N., Malheiros T.F., da Franca Rocha W.D.J.S. (2023). Energy recovery from biogas in domestic waste water treatment plant in the last 5 decades: A bibliometric analysis. *Journal of Scientometric Research*, 12(2), 343–256. <http://doi.org/10.5530/jscires.12.2.031>
32. Klimenko, N.A., Savchina, L.A., Kozyatnik, I.P., Goncharuk, V.V., Samsoni-Todorov, A.O. (2009). The effect of preliminary ozonization on the bioregeneration of activated carbon during its long-term service. *Journal of Water Chemistry and Technology*, 31(4), 220–226. <https://doi.org/10.3103/S1063455X09040031>
33. Montayev, S., Ongayev, M., Begaliev, R., Ryskaliev, M., Denizbayev, S. (2024). Sorption Treatment and Desalination of Mineralized Water Using Opoka to Reduce Hardness and Chloride Content. *International Journal of Design and Nature and Ecodynamics*, 19(5), 1733–1740. <https://doi.org/10.18280/ijdne.190527>
34. Laganà, P., Votano, L., Caruso, G., Azzaro, M., Lo Giudice, A., Delia, S. (2018). Bacterial isolates from the Arctic region (Pasvik River, Norway): assessment of biofilm production and antibiotic susceptibility profiles. *Environmental Science and Pollution Research*, 25(2), 1089–1102. <https://doi.org/10.1007/s11356-017-0485-1>
35. Kazimierowicz J., Dębowski M., Zieliński M. (2025). Innovative method for biomethane production based on a closed cycle of biogas upgrading and organic substrate pretreatment – Technical, economic, and technological fundamentals. *Energies*, 18(5), 1033. <https://doi.org/10.3390/en18051033>
36. Bermúdez L.A., Mendoza V.D., Díaz J.C.L., Pascual J.M., Martínez M.D.M.M., Capilla J.M.P. (2024). Investigation of the agricultural reuse potential of urban wastewater and other resources derived by using membrane bioreactor technology within the circular economy framework. *Science of The Total Environment*, 955, 177011. <https://doi.org/10.1016/j.scitotenv.2024.177011>
37. Capodaglio A.G. (2023). Urban wastewater mining for circular resource recovery: Approaches and technology analysis. *Water*, 15(22), 3967. <https://doi.org/10.3390/w15223967>
38. Mossa, M. (2006). Field measurements and monitoring of wastewater discharge in sea water. *Estuarine, Coastal and Shelf Science*, 68(3–4), 509–514. <https://doi.org/10.1016/j.ecss.2006.03.002>
39. De Serio, F., Mossa, M. (2016). Environmental monitoring in the Mar Grande basin (Ionian Sea, Southern Italy). *Environmental Science and Pollution Research*, 23(13), 12662–12674. <https://doi.org/10.1007/s11356-015-4814-y>
40. Seraya, N., Daumova, G., Petrova, O., Garcia-Mira, R., Polyakova, A. (2025). Ecological Status of the Small Rivers of the East Kazakhstan Region. *Sustainability (Switzerland)*, 17(14), 6525. <https://doi.org/10.3390/su17146525>
41. Alengebawy A., Ran Y., Osman A.I., Jin K., Samer M., Ai P. (2024). Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review. *Environmental Chemistry Letters*, 22(6), 2641–2668. <https://doi.org/10.1007/s10311-024-01789-1>
42. Garkoti P., Thengane S.K. (2025). Techno-economic and life cycle assessment of circular economy-based biogas plants for managing organic waste. *Journal of Cleaner Production*, 504, 145412. <https://doi.org/10.1016/j.jclepro.2025.145412>
43. Silva J.A. (2023). Wastewater treatment and reuse for sustainable water resources management: a systematic literature review. *Sustainability*, 15(14), 10940. <https://doi.org/10.3390/su151410940>
44. Rodrigues B.C.G., de Mello B.S., Grangeiro L.C., Dussan K.J., Sarti A. (2025). The most important technologies and highlights for biogas production worldwide. *Journal of the Air & Waste Management Association*, 75(2), 87–108. <https://doi.org/10.1080/10962247.2024.2393192>
45. Valujeva, K., Pilecka, J., Frolova, O., Berzina, L., Grinfelde, I. (2017). Measurement time estimation of CO₂, CH₄, N₂O and NH₃ in closed chambers and recirculation system with picarro g2508 analyser. *International Multidisciplinary Scientific Geo-Conference Surveying Geology and Mining Ecology Management, SGEM*, 17(41), 519–526. <https://doi.org/10.5593/sgem2017/41/S19.066>
46. Wani S.S., Parveez M. (2025). Quality and potential assessment of sewage sludge for clean energy utilization: a study from Srinagar City. *Biomass Conversion and Biorefinery*, 15, 19127–19142. <https://doi.org/10.1007/s13399-025-06580-y>
47. Rathore P., Killedar D.J., Parde D., Sahare A. (2022). Life cycle cost analysis of wastewater treatment technologies. *IOP Conference Series: Earth and Environmental Science*, 1032, 012006. <https://doi.org/10.1088/1755-1315/1032/1/012006>