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Agronomic Evaluation of Liquid Digestate from Thermophilic Biogas Plant as Foliar Fertilizer for Maize and Potato in Northern Kazakhstan

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ABSTRACT

The aim of the study was to investigate the influence of different doses of foliar feeding with liquid digestate from a biogas plant on the yield and biochemical parameters of maize and potato under the conditions of Northern Kazakhstan. A pilot-scale biogas unit was designed, assembled, and operated for livestock waste processing, and the resulting digestate was used in field experiments. The experimental design included a control (no fertilizer) and four doses of foliar digestate application: 50, 100, 150, and 200 L/ha with a spray solution volume of 300 L/ha. The digestate was characterized by neutral pH (7.4) and contained macronutrients (N – 1.4%, P_2O_5 – 1.1%, K_2O – 1.5%), indicating its potential as a nutrient source. For maize, the highest biomass yield was observed at 100 L/ha (38.76 t/ha), which exceeded the control (30.44 t/ha) by 27.3%. For potato, the maximum tuber yield was recorded at 200 L/ha (15.56 t/ha), compared to 14.03 t/ha in the control. The highest dry matter content in potato tubers (23.8%) was observed at 50 L/ha, compared to 20.4% in the control. Crude protein content in maize increased from 3.7% in the control to 4.4% at 100 L/ha. Nitrate concentration in potato tubers ranged from 56.4 to 63.5 mg/kg, remaining below the maximum allowable concentration (250 mg/kg). Radionuclide activity (^{137}Cs and ^{90}Sr) was several times lower than established safety limits. Statistical analysis showed no significant differences ($p > 0.05$); therefore, the observed effects are interpreted as trends. The results indicate a nonlinear crop response and the potential of digestate as a foliar fertilizer under Northern Kazakhstan conditions.

1. INTRODUCTION

In Kazakhstan, livestock farming is one of the fundamental sectors of the agro-industrial complex and is accompanied by the generation of significant volumes of organic waste [1]. Traditional methods of its storage and utilization increase the risk of soil and water pollution, as well as heighten the environmental burden on agricultural landscapes. According to Askarova et al. [2], millions of tons of agricultural waste are generated annually in Kazakhstan, with the potential manure production from animals estimated at 45,917.50 t/day, excluding poultry.

Particular interest lies in the processing of livestock waste using thermophilic anaerobic digestion technologies, which enhance the sanitary safety of the processed feedstock and yield a digestate with high agronomic value [3-5]. Modern biogas plants are becoming widespread due to their contribution to reducing landfill volumes and greenhouse gas emissions [6]. However, solutions are needed for the rational use of the by-product from biogas plants, which is mentioned in the scientific literature under various terms, including effluent [7], biofertilizer [8], digestate [9], biogas slurry [10], and effluent slurry [11].

During the separation of digestate, solid and liquid fractions with different chemical characteristics are formed [12]. According to Tambone et al. [13], the solid fraction of digestate can be used as an organic soil amendment because it is characterized by high dry matter and organic compound content. The liquid fraction is considered an effective fertilizer due to its high nitrogen and other nutrient content [14]. The work of Möller and Stinner [15] showed that digestate increases the availability of mineral nutrients for plants, such as nitrogen, phosphorus, and potassium, which is especially relevant for soils with low fertility. Digestate can partially replace mineral fertilizers and also stimulates soil biological activity and organic matter mineralization processes [16, 17].

In the study by Tambone et al. [18], a comparative assessment of the fertilizing properties of 23 organic matrices, including various types of digestate, composts, and manure, was performed. The authors found that digestates contain a significantly higher proportion of ammonium nitrogen (NH_4^+-N) and possess a higher degree of organic matter stabilization compared to compost and raw manure, ensuring their rapid mineralization and high nitrogen availability to plants. The fertilizing effect of digestate was comparable to that of NPK mineral fertilizers. Research by Robles-Aguilar et al. [19] demonstrates that the application of digestate promotes accelerated development of maize plants in the initial stages, increases leaf area, and enhances dry matter accumulation compared to treatments without organic fertilizers. Such effects are associated with increased ammonium nitrogen availability, improved soil water regime, and enhanced microbiological activity, providing plants with more favorable conditions for growth during early stages of organogenesis.

Data from studies by Toishimanov et al. [20], conducted in Southeastern Kazakhstan, confirm the general trend of increasing organic fertilizer efficiency. Experiments with maize and soybeans established that organic fertilizers improve soil agrochemical properties, increase yield, and simultaneously reduce the need for mineral fertilizers.

In the study by Kumar [21], the effect of digestate from sugar production waste on maize growth and productivity is presented. A field experiment involving six levels of digestate dilution (0-100%) showed that concentrations of 20-40% ensured optimal plant development, including increased height, leaf surface area, fresh and dry mass, as well as higher chlorophyll content. Growth inhibition was observed at doses of 60-100%. The highest yield and maximum cob length were noted at a 40% concentration, which the author associates with an optimal supply level of nitrogen, potassium, and a number of trace elements.

In the work by Barbosa et al. [22], the effectiveness of digestate from a biogas plant as a source of nutrients for maize cultivation under greenhouse conditions was evaluated. The digestate was obtained after the anaerobic digestion of maize silage. Over 30 days of cultivation, the aboveground and root dry mass indicators of maize, as well as the nitrogen, carbon, and phosphorus content in plant tissues in the digestate treatment, were comparable to the NPK treatment and exceeded the control.

Field experiments in Poland established that maize yield had a quadratic dependence on the digestate application rate, reaching a maximum of 9.2-11.5 t/ha at an optimal digestate rate of 0.56-0.66 t/ha (dry matter basis). The limiting factor for yield was insufficient nitrate nitrogen uptake due to magnesium and iron deficiency. Simultaneously, environmental risks were identified: cadmium content in the grain exceeded threshold values, and in a dry year, increased lead accumulation was noted, highlighting the necessity for strict control of doses and mineral balance when using digestate [23].

Field data on the use of anaerobic digestion products in potato cultivation show that the effect depends not only on the dose but also on the combination with mineral nitrogen and on the nutrient management system within the crop rotation [24]. In a three-year experiment (potato-wheat), the application of dry digestate in combination with nitrogen fertilizer led to a statistically significant increase in potato yield. The best result was obtained with a combined scheme (digestate share + reduced mineral nitrogen rate), which the authors interpret as a result of improved soil nutrition and properties while maintaining nitrogen availability during critical growth phases.

The study on the nitrogen fertilizing value of liquid fractions of organic fertilizers shows that the substitution value for mineral nitrogen for potatoes varies significantly between years and conditions, and also depends on application technologies and N losses, emphasizing the need for local dose calibration and control of the soil N regime when using liquid organic products [25].

Adamovičs et al. [26] presented the results of field studies on the use of alternative fertilizers based on biogas plant digestate for potato cultivation. The experiments used manure digestate combined with wood ash at rates of 15 and 30 t/ha. It was established that the application of these fertilizer mixtures ensured an increase in potato yield up to 34.2 t/ha when using pig digestate and up to 27.8 t/ha when using cattle digestate, as well as an increase in dry matter content in tubers by 1.7-2.7%.

Cepl et al. [27] noted that the use of biogas plant digestate in potato cultivation technology can be considered an effective alternative to traditional mineral nitrogen fertilizers. Field experiments conducted in 2014-2015 in the Czech Republic included three fertilizer treatments: application of 120 kg N/ha in the form of urea, 120 kg N/ha in the form of digestate, and an increased nitrogen rate of 180 kg N/ha. It was found that weather conditions significantly influenced potato yield and quality, especially in the dry year of 2015. In the more favorable, moisture-sufficient year of 2014, the use of digestate provided higher tuber yield compared to mineral nitrogen, with no negative impact on internal quality parameters. On average over the study years, the highest potato yield was observed with the application of digestate at a dose equivalent to 120 kg N/ha.

In the work by Kitaya et al. [28], the possibility of using digestate obtained from methane fermentation as a source of water and nutrients for growing sweet potatoes (Ipomoea batatas) on sandy soils was studied. The experiment used various dilution levels of digestate (from 1:80 to 1:20) and compared them with commercial nutrient solutions. It was established that the highest tuber growth rate was observed when using digestate diluted at a ratio of 1:20, which exceeded the indicators of both more concentrated options and the application of standard mineral nutrient solutions.

The effectiveness of digestate application strongly depends on soil and climatic conditions and nutrient availability, which requires regional adaptation of this technology. Northern Kazakhstan belongs to the risky farming zone and is characterized by unstable precipitation, frequent droughts, and limited moisture availability during the growing season, which significantly affects crop productivity and nutrient uptake from soil-applied fertilizers [29]. Annual precipitation in the region ranges from 250 to 350 mm, and moisture availability during the vegetation period is often insufficient for stable agricultural production, increasing the importance of adaptive fertilization strategies [30]. Under such conditions, foliar fertilization can be considered a promising approach, as it allows nutrients to be supplied directly to plant tissues and reduces dependence on soil moisture, which is especially important in drought-prone regions.

2. MATERIALS AND METHODS

2.1 Study objects and experimental designs

Biogas plant digestate is a by-product of anaerobic digestion of cattle manure.

Maize (*Zea mays* L.) hybrid “Pumori” belongs to the mid-early maturity group (FAO 220, Germany). It is characterized by resistance to low soil temperatures in the early development stages, good adaptability to stress, and stable productivity under risky farming conditions. Because of its moderate ripening period, the hybrid is suitable for both producing quality silage and grain. Plants form uniform ears and are characterized by resistance to adverse environmental factors.

Potato (*Solanum tuberosum* L.), variety "Gala" (Germany), is an early-ripening table variety, included in the State Register of the Republic of Kazakhstan in 2012. The plant is of medium height, semi-upright; tubers are elongated-oval with yellow skin and dark yellow flesh, with small eyes. The variety is characterized by stable yield (14.6-24.4 t/ha according to State Variety Testing data). It is distinguished by high resistance to foliage and tuber late blight, rhizoctonia, blackleg, potato virus Y, and moderate resistance to potato leafroll virus, which determines its suitability for cultivation and experimental studies in the conditions of Northern Kazakhstan.

The experimental designs for studying the effect of foliar feeding with digestate are presented in Table 1.

Table 1. Foliar digestate application rates used in the maize and potato experiments

No.	Digestate Rate	Application Method
1	0	Without fertilizers (control)
2	50 L/ha	Foliar application
3	100 L/ha	Foliar application
4	150 L/ha	Foliar application
5	200 L/ha	Foliar application

Foliar application of digestate was performed with a fixed spray volume of 300 L/ha. Digestate was diluted with water to obtain final application rates of 50, 100, 150, and 200 L/ha according to the experimental scheme. Plot area – 112 m^2 (5.6 m × 20 m). The experiment included five treatments: a control without fertilizer application and foliar application doses of liquid digestate: 50, 100, 150, and 200 L/ha. Each treatment was arranged in three field (spatial) replications represented by separate experimental plots within the same field. The plots were laid out systematically in consecutive strips.

2.2 Cultivation practices in the experiments

Pre-sowing tillage, sowing, and crop care for maize grown for silage were carried out according to the recommended technology: 1) Autumn tillage: disk harrowing to a depth of 12-14 cm; 2) Early spring harrowing at the stage of physical soil ripeness, tillage depth – 3-5 cm; 3) Seed treatment with fungicidal preparations (encrustation); 4) Pre-sowing cultivation to a depth of 4-5 cm; 5) Sowing in the second decade of May (16.05.2025). Sowing method: wide-row with 70 cm row spacing, seeding rate of 80 thousand seeds/ha. Seeding depth – 6-8 cm; 6) Pre-emergence harrowing: 4-5 days after sowing at a speed of 3-4 km/h (to control weeds and break the soil crust); 7) Inter-row cultivation to a depth of 7-8 cm; 8) Harvesting: at the milky-wax ripeness stage, chopping length – up to 2 cm. Cutting height – 6-7 cm. Digestate application for foliar feeding was carried out at the 6-8 leaf stage (spray solution volume of 300 L/ha).

Field experiments for potato cultivation were established in accordance with the recommended potato cultivation technology for the conditions of Northern Kazakhstan, adhering to common agronomic requirements. All field operations were performed within optimal agrotechnical timeframes. For planting, tubers of the medium fraction weighing 50-80 g were used. Pre-planting warm-up was conducted for 12 days at a temperature of 12-16 °C. Soil preparation included agrochemical soil testing, early spring harrowing, and plowing, followed by rototilling. Potato planting was conducted in the second decade of May (15.05.2025). Planting depth was 10 cm. The planting scheme was 70 × 40 cm (row spacing width – 70 cm, distance between plants in a row – 40 cm). During the growing season, 2 inter-row cultivations were performed before canopy closure. The final cultivation included hilling. Control of the Colorado potato beetle was carried out by insecticide treatment with Decis (active ingredient deltamethrin – 100 g/L) during the period of mass appearance of I-II instar larvae. Foliar feeding was applied once at the budding-beginning of the flowering stage (spray solution volume of 300 L/ha).

2.3 Measurements and observations

Quality parameters of the obtained digestate were determined using the following methods. The pH was measured potentiometrically in a salt suspension. Total nitrogen content was determined by the Kjeldahl method. Total phosphorus (P_2O_5) was determined by potentiometric titration of an acidified solution with sodium hydroxide within the interval from the equivalence point of monosodium phosphate to disodium phosphate. Potassium (K_2O) content was determined by the flame photometric method. Copper and zinc content were determined by atomic absorption spectrometry. The specific activity of natural (^{226}Ra, ^{232}Th) and technogenic (^{137}Cs, ^{90}Sr) radionuclides was measured using a scintillation gamma spectrometer. The assessment of natural radionuclide activity was carried out in accordance with national regulatory standards. The specific activity of natural radionuclides in fertilizers was evaluated using the criterion: $A_U + 1{,}5 \cdot A_{Th} \leq 1{,}0$ kBq/kg, where A_U is the specific activity of uranium-238 (represented by ^{226}Ra) and A_{Th} is the specific activity of thorium-232 (represented by ^{228}Th), assuming radioactive equilibrium within the uranium and thorium decay series.

An agrochemical survey of soils was conducted by collecting point samples using a soil auger to the depth of the arable layer, followed by the formation of a composite sample. Nutrient analyses followed standard methods: the Machigin method (for available P and K), the Tyurin–Nikitin method (for organic matter), and the Tyurin–Kononova method (for hydrolysable nitrogen). Soil pH was measured in a 1:5 water extract using a pH meter.

Yield of green and dry maize mass was determined for each treatment by harvesting a 5 m^2 area at the milky-wax ripeness stage. Plants were weighed with an accuracy of ±1 g to determine green mass yield, which was then converted to t/ha. Subsequently, a part of the sample (~1 kg) was chopped (±2 cm) and dried in a drying oven at 65 °C to a constant mass [31]. Crude protein mass fraction was determined by the Kjeldahl method. Crude ash was determined by treating the sample with hydrochloric acid and isolating the insoluble residue. Crude fiber was determined by a method based on removing acid- and alkali-soluble substances from the sample and weighing the residue, which was taken as fiber. Crude fat was determined by extraction with petroleum ether, removal of the solvent by distillation and drying, and weighing the obtained residue.

Potato yield was recorded from a central 5 m^2 area. The total tuber yield was determined by the mass of fresh tubers. For quality analysis, the dry matter content in tubers was determined by drying fresh tuber samples at 65 °C to a constant mass. Lead, cadmium, and arsenic contents were determined using the inversion voltammetric method after sample preparation. Mercury content was determined by atomic absorption spectrometry with Zeeman background correction. Nitrate and nitrite contents were determined by photometric analysis after aqueous extraction. Organochlorine pesticides were determined using chromatographic methods. Radionuclide activity was assessed by radiometric analysis.

Statistical processing of the experimental data was performed using the program STATISTICA (data analysis software system), version 10, StatSoft, Inc. (2011). Variability of the biochemical analysis parameters was determined by calculating the mean, coefficient of variation (*V*, %), and standard error of the mean (*Sx*). ANOVA was used with significance set at $p < 0.05$.

2.4 Meteorological conditions and characteristics of the experimental site

The experimental site is located in the hilly plain steppe zone of the Akmola Region, Zerendi District, Kazakhstan (Figure 1).

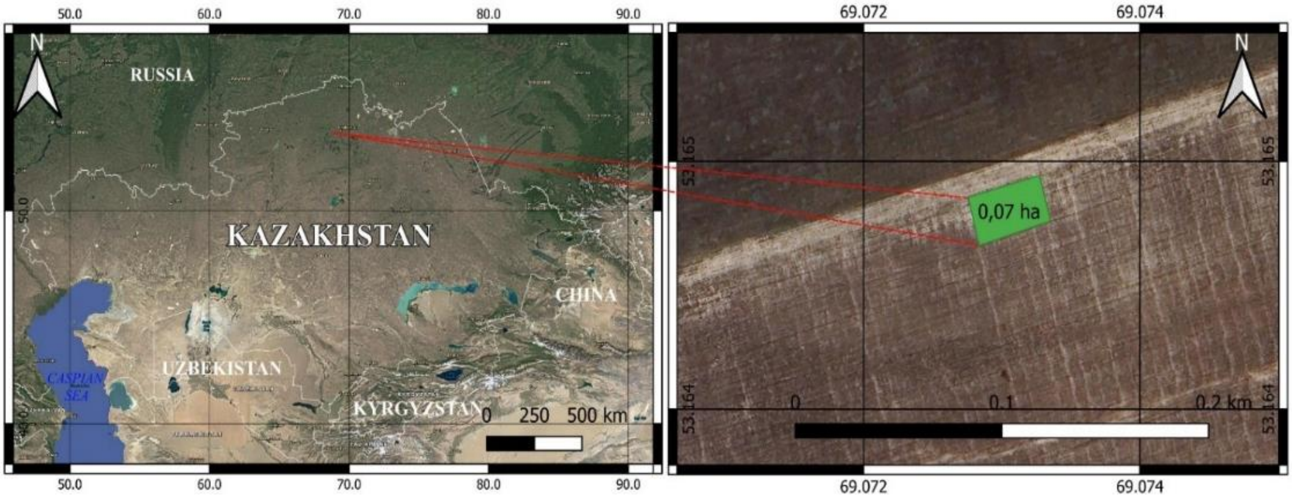

Figure 1. Location of the experimental site (53°09'54.0"N, 69°04'25.8"E)

Table 2. Agrochemical indicators of the experimental site

Crop	Depth (cm)	Content (mg/kg)				Humus (%)	pH
		NO_3	P_2O_5	K_2O	S		
Corn	0-20	2.5	106.8	1007.0	15.5	4.8	7.9
	20-40	3.5	60.8	1005.3	7.7	4.5	7.8
	Mean	3.0	83.8	1006.2	11.6	4.7	7.9
Potato	0-20	2.0	58.5	1056.0	9.9	4.7	7.9
	20-40	2.2	20.2	754.7	4.7	3.5	8.2
	Mean	2.1	39.4	905.3	7.3	4.1	8.1

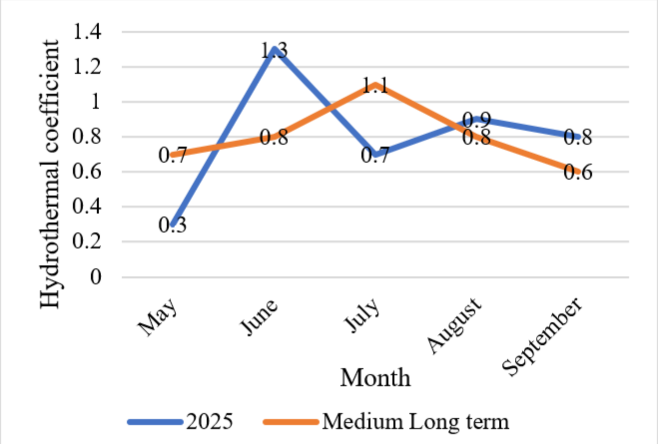

Figure 2. Hydrothermal coefficient (K) of Selyaninov for the growing season

The soil of the experimental site is classified as a moderately humic Chernozem with a humus horizon depth of 25-27 cm. Soil chemical properties were determined at depths of 0-20 and 20-40 cm (Table 2). The content of nitrate nitrogen in the 0-40 cm layer can be characterized as low, phosphorus as elevated, potassium as very high, and sulfur as medium. The soil reaction is neutral, with a pH of 7.8-8.2. The humus content in the soil is medium.

The meteorological conditions of 2025 were characterized as moderately favorable but with signs of moisture supply stress in early summer. The moisture deficit in the pre-vegetation period was partially compensated by summer precipitation.

For the experimental period (2025), data were used to calculate the hydrothermal coefficient (K) based on the Selyaninov formula: $K = (\Sigma P \times 10) / (\Sigma T \times d)$, where K is the monthly hydrothermal coefficient for the growing season, ΣP is the sum of monthly precipitation (mm), and ΣT is the sum of average daily temperatures (°C) for the given month (Figure 2).

The growing season (May-September), when average daily temperatures consistently exceeded +10 °C, was the primary period for crop formation. The total precipitation during this period was 283.3 mm, and the cumulative temperature sum was 2283.1 °C.

A sharp contrast between months is observed: in May, the coefficient was low at 0.3, followed by a sharp jump to 1.3 in June, and a decrease again from July onward. In 2025, the start of the season and the active period of biomass accumulation occurred under dry conditions, which affected plant development during critical vegetative phases and, ultimately, productivity.

3. RESULTS

3.1 Biogas plant technological scheme

The biogas plant was installed at a livestock (dairy) farm and was independently designed and assembled for experimental and applied research purposes. The installation is not a commercial or industrially manufactured system. Technological solutions, including the process layout, reactor configuration, and auxiliary units, were developed specifically for the on-site processing of livestock waste and the production of digestate at the dairy farm (Figure 3).

Figure 3. Biogas plant at a livestock farm

The technological scheme of the biogas plant is designed for the anaerobic processing of livestock waste to produce biogas and digestate. It includes a raw material reception system, a reactor block, a gas handling section, a biogas distribution and utilization system, as well as control, measuring, and safety devices (Figure 4).

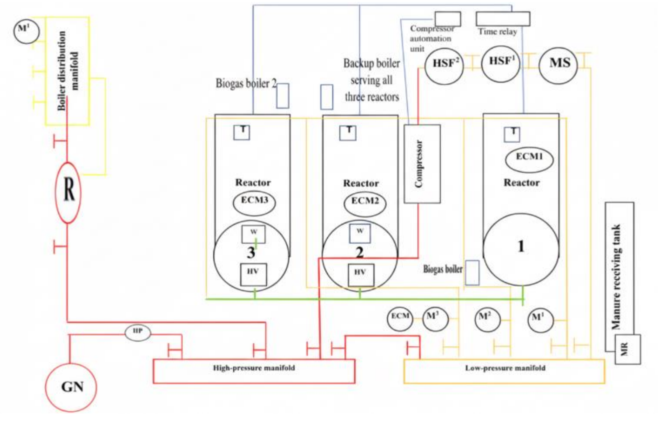

Figure 4. Technological process flow diagram of the biogas plant

Notes: R – reducing gear; GN – gas accumulator; ECM – electro-contact manometer; HP – high-pressure manometer; M – manometer; MS – moisture separator; HSF – hydrogen sulfide filter; W – window; T – temperature; HV – hydraulic valve; MR – manure intake motor-reducer.

The raw feedstock (cattle manure) enters a reception pit, equipped with a motor-reducer (MR) that supplies the substrate to the reactor system. Anaerobic digestion is carried out in three reactors, each equipped with a hydraulic valve (HV), solenoid valves (ECM1-ECM3), temperature sensors, and shut-off valves. Maintaining the required digestion process parameters is ensured by a temperature and pressure control system.

The generated biogas is extracted from the reactors through a pipeline system and enters a gas holder (GN), where it is temporarily stored, and its pressure is equalized. Before being supplied to end users, the biogas is cleaned in hydrogen sulfide filters (HSF1, HSF2) and a moisture separator (MS), which reduces the content of moisture and sulfur compounds.

To ensure a stable biogas supply, the system includes low-pressure and high-pressure collectors, as well as a boiler supply manifold. Gas pressure is monitored using pressure gauges (M, HP) and an electrical contact pressure gauge (ECM). The system is equipped with pressure regulators, ensuring safe operation.

Biogas is utilized in dedicated biogas boilers. Additionally, a reserve boiler is provided to maintain the operation of all three reactors if necessary. A compressor equipped with automation and a time relay, providing a regulated operating mode, is used for gas supply.

The scheme includes shut-off valves, inspection windows (W), and a system for monitoring temperature parameters, enabling safe and continuous operation of the plant. The set of technical solutions ensures the reliable functioning of the biogas system, control over technological parameters, and the production of a stable volume of biogas and digestate for subsequent use in energy and agrotechnological applications.

3.2 Chemical composition and properties of the digestate

The chemical composition of the biogas plant digestate indicates its agronomic value while simultaneously highlighting the necessity for its regulated application, considering environmental limitations. The digestate's pH is 7.4, corresponding to a neutral reaction. This pH level is favorable for most agricultural crops (Table 3).

Table 3. Chemical composition of the digestate (fresh weight basis)

Parameters	Actual Value
pH	7.4
N (%)	1.4
P_2O_5 (%)	1.1
K_2O (%)	1.5
Zn (%)	0.3
Cu (%)	0.03
Natural radionuclides (Bq/kg)	12.2
^{232}Th (Bq/kg)	4.6
^{226}Ra (Bq/kg)	5.3
Technogenic (artificial) radionuclides	
^{137}Cs (Bq/kg)	26.3
^{90}Sr (Bq/kg)	37.2

The mass fractions of nutrients in the fresh liquid digestate were 1.4% for nitrogen (N), 1.1% for phosphorus (as P2O5), and 1.5% for potassium (as K2O), expressed on a fresh weight basis. This demonstrates the digestate's ability to partially meet plant nutrient requirements. Regarding macronutrient content, the digestate can be considered an organic fertilizer capable of partially replacing mineral NPK forms or being used in combination with them. The content of microelements in the digestate requires a more balanced assessment. The zinc concentration is 0.3%, and copper is 0.03%. The presence of these elements is a positive factor, as Zn and Cu are essential microelements. However, the higher Zn content indicates a potential risk of its accumulation in the soil with systematic digestate application, especially on light soils or when recommended application rates are exceeded. In this regard, the use of digestate should be accompanied by agrochemical monitoring of heavy metal content in both soil and plant products.

The results of radiological analysis indicate the presence of both natural and technogenic radionuclides. The specific activity of natural radionuclides ^{232}Th and ^{226}Ra is 4.6 and 5.3 Bq/kg, respectively, which typically reflects the natural radiation background of the original organic feedstock. At the same time, the presence of technogenic radionuclides ^{137}Cs and ^{90}Sr with specific activities of 26.3 and 37.2 Bq/kg, respectively, has been recorded. The presence of these isotopes necessitates mandatory comparison with current sanitary-hygienic standards and an assessment of their potential migration into soil and plants. From a scientific standpoint, this does not preclude the use of the digestate; however, it underscores the necessity for strict dosage regulation, as well as monitoring of soil and product radiological safety when used in agrotechnologies.

3.3 Yield of potato and maize under different application rates

Table 4 presents the results of the maize productivity assessment under different digestate application rates (foliar feeding). The application of digestate at a rate of 50 L/ha resulted in higher mean biomass yield values by 13.1%, ear yield by 14.5%, and dry matter output by 11.5% compared to the control. The dry matter content was 42.00%, which is 1.4% lower than the control, indicating no substantial changes in biomass structure with a moderate increase in yield.

Table 4. Maize yield and its structure depending on foliar feeding with digestate (2025)

Treatment	Yield (t/ha)			Dry Matter Content (%)
	Biomass	Ears	Dry Matter Yield	
Control	30.44	14.26	13.0	42.60
50 L/ha	34.44	16.33	14.5	42.00
100 L/ha	38.76	18.43	16.0	41.20
150 L/ha	33.50	16.79	14.8	44.20
200 L/ha	32.02	16.12	14.3	44.60

The highest mean values for all productivity indicators were observed with the application of digestate at a rate of 100 L/ha. This treatment recorded the highest biomass yield, 38.76 t/ha, which was 27.3% higher than the control; ear yield numerically exceeded the control by 29.3%. Dry matter output was 23.1% higher than the control. Simultaneously, the dry matter content decreased to 41.20%, which is 3.3% below the control level.

With a further increase in the digestate rate to 150 L/ha, the biomass yield decreased relative to the 100 L/ha treatment and amounted to 33.50 t/ha, but numerically remained higher than the control 10.1% higher than the control. The ear yield in this treatment numerically exceeded the control by 17.7%. The dry matter output reached 14.8 t/ha, which is 13.8% higher than the control. A significant feature of this treatment was an increase in dry matter content by 3.8% above the control value, indicating the formation of drier biomass with a somewhat lower total yield.

In the treatment with an application rate of 200 L/ha, the biomass yield was 32.02 t/ha, numerically exceeding the control by 5.2%. Ear yield was 13.0% higher than the control. Dry matter yield exceeded the control by 10.0%. At the same time, the dry matter content was the highest among all treatments, reaching 44.60%, which is 4.7% above the control level. This combination of a moderate yield increase with high dry matter content may indicate a shift in plant response from predominantly increasing green mass to more intensive accumulation of dry residue and structural substances.

Table 5 presents the results of the potato productivity assessment under foliar application of digestate at rates of 50-200 L/ha in terms of tuber yield and dry matter content. In the control treatment, tuber yield was 14.03 t/ha with a dry matter content of 20.4%. Application of digestate at 50 L/ha showed a slight increase in mean yield values of 2.4%, while the most notable change was in product quality: dry matter content reached 23.8%, which is 16.7% higher than the control. Thus, with a minimal increase in tuber mass, the 50 L/ha treatment demonstrated an effect on dry matter accumulation.

Table 5. Potato yield depending on foliar feeding with digestate (2025)

Treatment	Tuber Yield (t/ha)	Deviation from Control ±	Dry Matter (%)
Control	14.03		20.4
50 L/ha	14.36	+0.33	23.8
100 L/ha	14.66	+0.63	22.6
150 L/ha	14.54	+0.51	20.9
200 L/ha	15.56	+1.53	21.3

In the 100 L/ha treatment, the yield was 4.5% higher than the control. The dry matter content was 22.6%, which is 10.8% higher than the control. Compared to the 50 L/ha dose, the yield increase was more pronounced; however, the quality in terms of dry matter content decreased slightly, indicating a different direction in the crop's response.

In the 150 L/ha treatment, the yield exceeded the control by 3.6%, meaning it was lower than at 100 L/ha, which confirms the nonlinear nature of the dose-response relationship. The dry matter content in this treatment reached 20.9%, which is 2.5% higher than the control but significantly lower than in the 50-100 L/ha treatments.

The highest tuber yield was obtained at the 200 L/ha rate, where the indicator reached 15.56 t/ha. The increase relative to the control was 1.53 t/ha, or 10.9%, which is the highest value among all treatments and demonstrates the ability of an increased digestate dose to enhance yield formation. However, the dry matter content in this treatment was 21.3%, which is 4.4% higher than the control but notably lower than in the 50 L/ha treatment and also lower than in the 100 L/ha treatment. According to the analysis of variance, no statistically significant differences between treatments were found ($p > 0.05$); therefore, the observed differences are interpreted as numerical trends and should be considered as indicative rather than conclusive. Overall, the response of both maize and potato to digestate application was nonlinear; however, the lack of statistical significance indicates that these effects should be interpreted with caution.

3.4 Biochemical analysis of maize and potato under different digestate application rates

Foliar treatment of maize crops with digestate at rates of 50-200 L/ha induced a dose-dependent but nonlinear response in biochemical indicators (Table 6). The fat content in the green mass varied from 5.3% to 11.6%, reaching its maximum at the 150 L/ha dose. Ash content remained stable across all treatments (1.5–1.6%). It was established that the 100 L/ha dose stimulated nitrogen metabolism, with crude protein content increasing by 18.9% relative to the control. However, when the dose was increased to 150–200 L/ha, the protein content decreased to 3.1% compared with the control. Conversely, phosphorus accumulation showed a consistently positive trend, increasing from 0.10 to 0.18%. Crude fiber content was highest in the 100 L/ha treatment, indicating accelerated formation of mechanical tissues. The accumulation of nitrates and nitrites showed a fluctuating pattern, with minimal values observed at the 150 L/ha dose. Statistical analysis of biochemical indicators showed different levels of variability across traits. The coefficient of variation (*V, %*) ranged from 2.89% to 26.71%, indicating low variability for ash (3.56%) and crude fiber (2.89%), moderate variability for nitrates (6.10%) and nitrites (13.39%), and increased variability for crude protein (14.96%), phosphorus (23.36%), and fat (26.71%). The standard error of the mean (*Sx*) ranged from 0.01 to 1.12, with the lowest values for phosphorus (0.01) and ash (0.02), and higher values for crude protein (0.24), crude fiber (0.29), and fat (1.12), reflecting the degree of dispersion of biochemical traits under different digestate doses. Analysis of potato tubers (Table 7) showed improved quality characteristics while maintaining full sanitary safety. The application of digestate at doses of 50-100 L/ha contributed to an increase in dry matter content to 22.6-23.8% (compared to 20.4% in the control). Safety parameters in all treatments were significantly below the maximum allowable concentration (MAC).

Table 6. Biochemical analysis of maize in green biomass (2025)

Indicator (%)	Control	50 L/ha	100 L/ha	150 L/ha	200 L/ha	*V, %*	*Sx*
Fat	10.3	5.3	8.7	11.6	10.8	*26.71*	*1.12*
Ash	1.6	1.6	1.5	1.5	1.5	*3.56*	*0.02*
Crude protein	3.7	3.7	4.4	3.1	3.1	*14.96*	*0.24*
Crude fiber	21.9	22.5	23.6	22.6	23.2	*2.89*	*0.29*
Calcium			< 0.01				
Phosphorus	0.10	0.12	0.12	0.15	0.18	*23.36*	*0.01*
Nitrates	1.32	1.22	1.34	1.19	1.37	*6.10*	*0.04*
Nitrites	0.63	0.57	0.73	0.52	0.68	*13.39*	*0.04*

Notes: *V* – coefficient of variation; *Sx* – standard error of the mean.

Table 7. Biochemical analysis of potatoes (2025)

Indicator	Control	50 L/ha	100 L/ha	150 L/ha	200 L/ha	MAC	*V, %*	*Sx*
Dry matter (%)	20.4	23.8	22.6	20.9	21.3		*6.35*	*0.62*
Toxic elements (mg/kg):								
Lead	0.022	0.026	0.020	0.037	0.18	0.5	*121.18*	*0.03*
Cadmium			Not detected			0.03		
Arsenic	0.046	0.052	0.037	0.029	0.055	0.2	*24.56*	*0.00*
Mercury			Not detected			0.02		
Nitrates (mg/kg)	56.4	60.8	63.5	60.2	58.4	250	*4.45*	*1.19*
Pesticides (mg/kg):								
Hexachlorocyclohexane (α-, β-, γ-isomers)			less than 0.005			0.1		
DDT and its metabolites			less than 0.005			0.1		
Radionuclides (Bq/kg):								
Cesium-137	8.36	9.69	7.56	10.26	7.69	80	*13.88*	*0.54*
Strontium-90	5.47	4.29	4.11	3.29	4.03	40	*18.58*	*0.35*

Notes: MAC – maximum allowable concentration; *V* – coefficient of variation; *Sx* – standard error of the mean.

Lead and arsenic contents were significantly below the permissible level. Cadmium and mercury were not detected. The nitrate concentration (56.4–63.5 mg/kg) was four times lower than the standard (250 mg/kg). Residual amounts of organochlorine pesticides were not detected. The specific activity of Cesium-137 and Strontium-90 was 7-12 times lower than the maximum permissible levels. Statistical analysis of dry matter, heavy metals, nitrates, and radionuclides revealed different levels of variability among indicators. The coefficient of variation (V, %) ranged from 4.45% to 121.18%. Low variability was observed for nitrates (4.45%) and dry matter (6.35%), indicating stable values across treatments. Moderate variability was recorded for cesium-137 (13.88%) and strontium-90 (18.58%), while arsenic showed increased variability (24.56%). The highest variability was observed for lead (121.18%), indicating strong dispersion of values among treatments. The standard error of the mean (*Sx*) ranged from 0.00 to 1.19, with minimal values for arsenic (0.00) and lead (0.03), and higher values for nitrates (1.19) and cesium-137 (0.54), reflecting differences in the stability of the studied indicators under various digestate doses.

Foliar application of digestate within the range of 50–100 L/ha is optimal for enhancing the feed value (protein content) of maize and the quality (dry matter content) of potatoes. Increasing the dose to 200 L/ha is advisable for maximizing phosphorus accumulation, while ensuring the production of environmentally safe produce is guaranteed across all investigated dose ranges.

4. DISCUSSION

Slepetiene et al. [32] reported that liquid digestate contains 9.70-14.8% total nitrogen, 1.66-2.44% total phosphorus, and 5.78-9.24% total potassium on a dry matter basis, which is significantly higher than the values obtained by Rolka et al. [33] for liquid digestate produced primarily from pig manure and maize silage (total N – 0.46%, P – 0.36%, K – 3.93% on a fresh weight basis). Such wide ranges of element content in liquid digestate are also confirmed by other studies. A review by Nowak and Czekała [34] showed that total nitrogen content in liquid digestate can vary from 0.29 to 0.75% of dry matter, phosphorus from 0.03 to 0.05%, and potassium from 0.50 to 0.62% for biogas plants operating on manure and silage. According to compiled literature data, the ranges of macronutrient content in digestate can be even wider and depend significantly on the type of feedstock. Nitrogen content varies from 0.06 to 1.24% of dry matter from food waste processing, from 0.21 to 7.8% from the organic fraction of municipal solid waste, from 0.14 to 2.1% from agricultural waste, and from 0.05 to 0.62% from manure. At the same time, digestate typically contains limited amounts of phosphorus (up to 2.4% dry matter) and potassium (up to 4.0% dry matter) [35, 36]. Thus, the composition of liquid digestate is characterized by high variability and is determined not only by the feedstock type but also by the technological regime of anaerobic digestion, the conditions of fraction separation, and the depth of organic matter decomposition. The results obtained fit well within the ranges described in the literature, while examples with elevated element concentrations demonstrate the potential of liquid digestate as a concentrated source of nutrients with efficient processing of organic feedstock.

For maize, the positive effect of digestate on early development stages was confirmed by Robles-Aguilar et al. [19], where digestate application increased above-ground biomass up to 3.5 times on sandy substrate and 1.5 times on field sand compared to the control. The maximum increase in biomass yield was up to 27%, indicating a pronounced positive effect of digestate, although it is less pronounced on soils with higher inherent fertility. Data from Kumar [21] showed optimal maize growth at a 40% concentration of digestate, while higher doses caused growth inhibition, reflecting the dependence of the effect on the application rate. Analysis of shoot and root dry mass of maize upon digestate application with a composition similar to that of mineral fertilizers showed similar biomass indicators, exceeding the control [22], confirming that digestate with a similar chemical composition exerts a positive fertilizing effect comparable to mineral fertilizers. The crude protein content of maize biomass in the present study (3.1-4.4%) falls within the lower range of variability reported in the literature and can be explained by genotype, nitrogen supply, and environmental conditions. Large-scale analyses of maize silage indicate that crude protein typically varies from approximately 4.7% to 10.5%, with mean values around 7.7% [37], reflecting substantial natural variability of this parameter. It is well established that crude protein content in maize is strongly dependent on nitrogen availability, with reduced values observed under limited nutrient input or abiotic stress. In addition, protein concentration may vary depending on hybrid characteristics and maturity stage [38]. Under moisture-limited conditions, such as those typical of Northern Kazakhstan, nitrogen uptake and assimilation may be constrained, which can contribute to lower protein accumulation [39]. Therefore, the obtained values can be interpreted as a combined effect of genotype, nitrogen availability, environmental conditions, and the foliar mode of nutrient application.

Field experiments show that the application of biogas plant digestate contributes to increased potato yield, especially when combined with mineral nitrogen. In a three-year experiment, combined application of dry digestate and a reduced N rate provided a statistically significant increase in tuber yield, with maximum indicators achieved at digestate doses of 15-30 t/ha [26]. Similar results were noted by Cepl et al. [27], where digestate application equivalent to 120 kg N/ha provided tuber yield equal to or higher than mineral nitrogen, without deteriorating product quality. The studies reviewed showed increases in yield and tuber dry matter content comparable to the results of the present work, where liquid digestate application provided yield increases of up to 10.9% and dry matter increases of up to 16.7%, depending on the rate. However, the effectiveness of organic fertilizers depends on weather conditions, application technology, and nitrogen losses [25], which underscores the need for local dose calibration.

The absence of statistically significant differences among treatments can be explained by the relatively high variability under experimental conditions, which reduces statistical power, as well as by the limited number of replications. A similar pattern, where higher mean values are observed without statistically significant differences, has been reported in digestate studies. For example, in a maize-based system, the application of digestate resulted in variations in growth and yield parameters that were not statistically significant despite observable differences between treatments [40]. Likewise, experiments with different digestate types showed higher biomass values in some treatments; however, these differences were not statistically significant due to increased variability of the data [41]. At the same time, the yield response demonstrated a nonlinear pattern, with maximum values observed at intermediate application rates. Such responses are consistent with previous findings, where maize yield showed a quadratic relationship with digestate rate, indicating the existence of an optimal application level rather than a linear increase [23]. This suggests that digestate acts as a supplementary nutrient source, where moderate doses improve plant performance, while higher rates do not result in proportional yield increases, and the relatively high background soil fertility may have further masked treatment effects.

5. CONCLUSION

Digestate from the biogas plant is characterized by a moderate content of macronutrients and can be considered as an additional plant nutrition source. A positive numerical trend was observed at the 100 L/ha rate for maize and at the 50–100 L/ha range for potato; however, further multi-year studies are required to confirm these patterns statistically. Higher application rates did not provide additional advantages. Overall, the results indicate the potential of digestate as a safe organic fertilizer under Northern Kazakhstan conditions.

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