

COMBINED EFFECTS OF HEAVY METAL IONS (Fe^{3+} - Cu^{2+} , Fe^{3+} - Zn^{2+} , Fe^{3+} - Cr^{3+} , Cu^{2+} - Zn^{2+} , Cu^{2+} - Cr^{3+} AND Zn^{2+} - Cr^{3+}) ON THE PRODUCTIVITY OF BIOGAS AND BIOMETHANE PRODUCTION

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Abstract. Background. Determining the effect of combined metal action on the anaerobic microbial association during the fermentation process and methane production.

Objective. To investigate the effect of the simultaneous interaction of heavy metal ions (Zn - Fe , Zn - Cu , Zn - Cr , Fe - Cu , Fe - Cr , Cu - Cr) on the process of biogas production and methane formation in it.

Methods. A laboratory study performed under conditions approximating industrial biogas production, involving the application of heavy-metal-ion salts and the measurement of the quantitative and qualitative composition of the final product.

Results. The combined effect of two heavy-metal ions on biogas production by an anaerobic microbial association is specific: the synergy of certain metal ions may stimulate the biosynthesis of biomethane while simultaneously inhibiting biogas production. In particular, Fe (20 mg/dm^3) – Cu (40 mg/dm^3) and Fe (20 mg/dm^3) – Cr (10 mg/dm^3) exhibit a slight positive effect on biogas yield compared to the control, whereas the interaction of these metal ions with Zn (5 mg/dm^3) reduces the biogas yield but improves its qualitative composition — the methane content increases.

Conclusions. The combined effect of two heavy-metal ions generally reduces biogas production compared to the control; however, it stimulates the production of a higher methane content in the biogas. Compared with the effect of a single heavy metal, the combined exposure does not have a positive impact on biogas production, which is attributed to the elevated concentrations of metal ions used in the experiment.

Keywords: heavy metal; Iron; Zinc; Copper; Chromium; biogas; biomethane.

Introduction

The availability and balance of trace elements in substrates for anaerobic digestion play a crucial role in determining the efficiency and stability of biogas production. This issue becomes particularly pronounced in biogas plants operating on uniform (mono) feedstocks, such as corn silage, barley, or other cereal residues, which are often characterized by an insufficient or imbalanced microelement composition. Under such conditions, deficiencies in essential trace elements may limit microbial activity and reduce methane yields, even when organic loading and operational parameters are optimized.

In addition to natural nutrient limitations, anthropogenic factors increasingly influence the elemental composition of biomass used for anaerobic digestion. In Ukraine, extensive agricultural areas have been affected by military activities, resulting in soil contamination with heavy metals and their subsequent accumulation in crops used as biogas substrates [1, 2]. Feedstock selection for biogas plants is typically

driven either by the need to utilize available waste streams (e.g., manure, slurry, distillery stillage) or by the feasibility of cultivating energy crops within a 30–50 km radius of the facility [3, 4]. These contrasting scenarios create fundamentally different conditions for trace element availability during fermentation.

When multiple substrates are co-digested, the resulting mixture often compensates for individual nutrient deficiencies, reducing or eliminating the need for additional trace element supplementation [4, 5]. In contrast, mono-digestion systems frequently require external supplementation due to several interrelated factors, including cultivation of energy crops on nutrient-depleted soils, inherently low microelement content in manure derived from animals fed on such biomass, and nutrient losses occurring during feedstock processing, particularly during ensiling [6–11]. For example, sod-podzolic soils prevalent in large regions of Ukraine are characterized by critically low levels of molybdenum and nickel, elements essential for key enzymatic reactions in anaerobic fermentation [7].

At the same time, the presence of heavy metals in substrates introduces an additional layer of complexity. Depending on their concentration, chemical form, and interactions, metal ions may either stimulate or inhibit anaerobic microbial processes [9, 12]. Numerous studies have demonstrated that appropriate supplementation with limiting trace elements can increase biogas yield by 5–7% and significantly enhance methane content. In particular, iron, copper, and chromium have been reported to stimulate biogas production within specific concentration ranges, whereas zinc, despite its essential role in methanogenesis, may exert inhibitory effects when applied individually at elevated concentrations [13].

While the influence of individual metal ions on anaerobic digestion has been extensively investigated [13–16], substantially less attention has been paid to their simultaneous presence and interaction. In practical biogas systems, microorganisms are rarely exposed to single metals in isolation; instead, they encounter complex mixtures of trace and heavy elements whose combined effects may differ markedly from those observed for individual ions. Existing studies addressing multi-element interactions remain limited and often focus on specific substrates or narrow concentration ranges [17–19], leaving significant gaps in understanding the synergistic or antagonistic effects of combined metal supplementation.

Against this background, the present study aims to investigate how the simultaneous presence of selected metal ions affects biogas yield and methane content during anaerobic digestion of cattle manure under mesophilic conditions. By examining both individual and combined effects of iron, copper, zinc, and chromium at environmentally and technologically relevant concentrations, this work seeks to contribute to a more realistic assessment of metal–microorganism interactions in anaerobic fermentation systems and to support the rational design of trace element supplementation strategies for biogas production.

Materials and Methods

Microorganism consortium. For the study, a microorganism consortium was prepared using a suspension (inoculum) derived from fresh manure of a free-range cow. The microbial consortium used in this research consisted of bacterial phyla predominant in fresh solid cattle manure, namely *Firmicutes*, *Bacteroidota*, and *Proteobacteria*, which correspond to the general “core” of the bovine bacterial microbiome, although the specific taxonomic composition of the microbiota was not directly analyzed within the scope of this research [20]. Prior to preparing the suspension, the main parameters of the manure were determined (Table 1): dry matter (DM [21], organic matter (OM) [22], ash content (A) [23], and pH

using a stationary laboratory ionometer MI-150. To prepare the suspension, 1 kg of manure was placed into a 5 L plastic bottle, and 3.6 L of distilled water was added. The mixture was manually homogenized, and pH was measured (pH range 6.5–7.5). The bottle was then incubated in a TC-80M thermostat (dark conditions, 37 ± 1 °C) for 60 days, periodically releasing the biogas formed and manually mixing the medium with oscillatory movements.

Anaerobic fermentation with metal ions. To study the effect of metal ions on the anaerobic fermentation process, laboratory methanogenic reactors with a working volume of 1.5 dm³, a 70% filling factor, and a wet-type gas holder were used. The concentration of the organic substrate in the reactor was 8% of the loading based on dry matter, with moisture content of 90%. For each reactor, 300 g of manure, 200 mL of homogenized inoculum, 200 mL of distilled water, and the required concentration of the metal salt (Table 1) were added. The mixture was homogenized, and pH was measured (if necessary, adjusted to 7 with 0.1 M NaOH or HCl). The sealed reactor was placed in a thermostat at 37 ± 1 °C, and the medium was mixed daily. Biogas yield parameters were recorded throughout the experimental period of 14 days.

Biogas and methane measurement. The quantitative composition of biogas was determined visually based on the difference in initial readings in a graduated wet-type gas holder. The qualitative composition of biogas was assessed at the peak biogas production on day 7. Methane content in the biogas was measured using a SAZQ gas analyzer (China).

Statistical analysis. All experiments were performed in triplicate ($n = 3$) to ensure reproducibility. Data are presented as the mean \pm standard deviation (SD). On the graphs, error bars represent a standard error of 5% of the mean. Statistical significance of differences between experimental groups was evaluated using one-way analysis of variance (ANOVA) in Microsoft Excel. Differences were considered statistically significant at $p < 0.05$.

Table 1: Concentration of metal ions in an anaerobic environment

Metal Ion Source	Experimental Concentration, mg/dm ³
Fe ³⁺ : FeCl ₃ ·6H ₂ O	20
Cu ²⁺ : Cu(NO ₃) ₂ ·6H ₂ O	40
Zn ²⁺ : ZnSO ₄ ·7H ₂ O	5
Cr ³⁺ : Cr ₂ (SO ₄) ₃ ·6H ₂ O	10

Results

After 60 days of fermentation, the inoculum was sampled to determine dry matter (DM), organic matter (OM), ash content (A), and pH (Table 2). The parameters of cattle manure (DM, OM, A) are presented in Table 2.

The task of the study was to investigate the combined effect of rational doses of individual elements for several microelements and their effect on biogas and biomethane production, in particular:

- Fe³⁺ (20 mg/dm³) in combination with Cu²⁺ (40 mg/dm³), Zn²⁺ (5 mg/dm³) and Cr³⁺ (10 mg/dm³);
- Zn²⁺ (5 mg/dm³) in combination with Cu²⁺ (40 mg/dm³) and Cr³⁺ (10 mg/dm³);
- Cu²⁺ (40 mg/dm³) in combination with Cr³⁺ (10 mg/dm³).

1. Effect of Fe³⁺ ions in combination with other metal ions. The influence of iron ions in combination with other elements on the anaerobic digestion of cattle manure is shown in (Fig. 1). A sample without the addition of metal ions served as the experimental control. The combined effect of iron with copper and iron with chromium, compared to the control (without added metals), was positive. However, compared to the effect of iron ions alone, all samples exhibited a lower biogas yield.

2. Effect of Cu²⁺ ions in combination with other metal ions. The combined effect of copper ions with other metals on the anaerobic digestion of cattle manure is presented in (Fig. 2). Among the various metal ion pairs, the combination of copper and iron produced the highest biogas yield, whereas the copper–zinc pair resulted in the lowest yield. The effect of copper ions alone on biogas production exhibited a significantly better dynamic, even compared to the control (sample without added metal ions).

3. Effect of Zn²⁺ ions in combination with other metal ions. The combined effect of zinc ions with other metals on the anaerobic digestion of cattle manure is shown in (Fig. 3). The effect of zinc ions alone, as well as in combination with iron, copper, or chromium, exhibited a negative trend in biogas yield. However, an increase in methane content in the biogas was observed, despite the reduction in overall biosynthesis productivity of the main product.

4. Effect of Cr³⁺ ions in combination with other metal ions. The combined effect of chromium ions with other metals on the anaerobic digestion of cattle manure is shown in (Fig. 4). Samples containing chromium exhibited a slight increase in biogas yield when combined with iron compared to the control. However, compared to the individual effect of chromium, the biogas yield was lower under the combined action of

metal pairs. The lowest biogas yield was observed for the chromium–copper combination.

Discussion

Justification of the research experiment

This study was designed to evaluate the combined effects of metal ions (Fe³⁺, Cu²⁺, Zn²⁺, Cr³⁺) on the anaerobic digestion of cattle manure. All experiments were performed in triplicate to ensure reproducibility, and biogas and methane yields were quantitatively monitored over a 14-day fermentation period. The microbial consortium was obtained from fresh free-range cow manure, providing a representative anaerobic microbial community capable of biogas production under conditions comparable to those of industrial-scale anaerobic digestion.

Mesophilic conditions (37 ± 1 °C) were selected to ensure controlled and stable evaluation of biogas and methane yields in batch reactors. The applied metal ion doses were selected based on concentration ranges previously reported to stimulate methanogenic activity while remaining below known inhibitory thresholds. This experimental design enables the identification of both synergistic and inhibitory interactions between metal ions, providing new insights into their combined effects on anaerobic digestion, which have not been previously described in the scientific literature.

Discussion and interpretation of the results

The results of the study indicated that the most positive effect on the anaerobic digestion process was observed for the combination of iron ions (Fig. 1 and Fig. 2) with copper ions, while a slightly lower effect was noted for the combination of iron and chromium ions (Fig. 1 and Fig. 4). The Fe³⁺–Cu²⁺ interaction exhibited the highest biogas production peak on days 6–7 of fermentation, with a biogas yield 9.7% higher than that of the control. Moreover, due to the effect of copper ions, the methane content throughout the fermentation period was 22% higher than in the control, with 63.8% methane in the experimental sample compared to 55% in the control.

Table 2: Raw material and inoculum parameters

Parameter	Cattle manure	Inoculum
DM, %	16.49±0.82	1.54±0.08
OM, %	13.66±0.68	1.00±0.05
A, %	17.17±0.85	34.71±1.74
pH	7.2±0.36	7.7±0.39

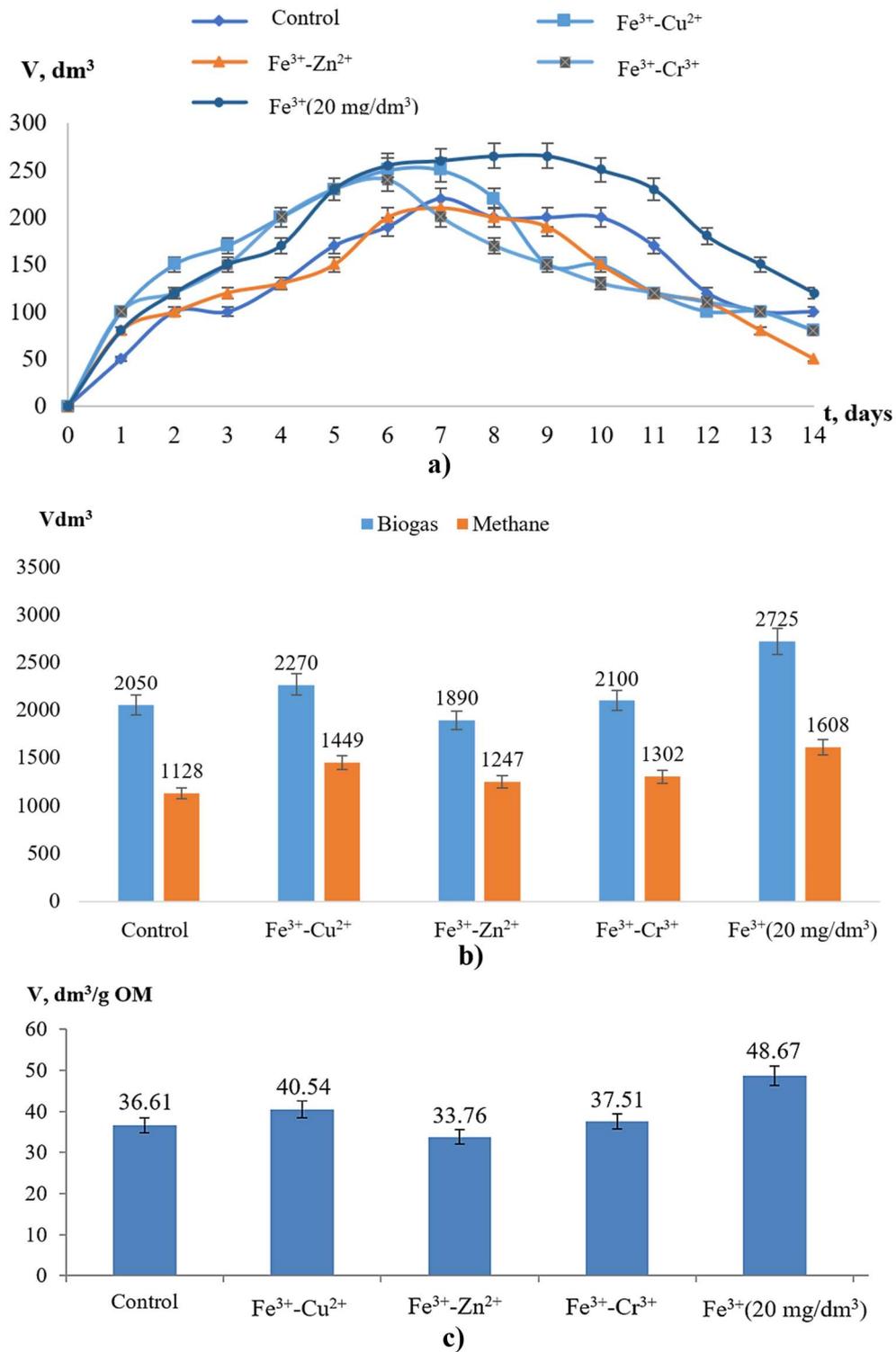


Figure 1. a) Daily biogas yield (V) under the combined effect of Fe³⁺ ions (20 mg/dm³) with Cu²⁺ (40 mg/dm³), Zn²⁺ (5 mg/dm³), and Cr³⁺ (10 mg/dm³); b) Total biogas (V) and methane (V) yield over 14 days of digestion under the combined effect of Fe³⁺ ions (20 mg/dm³) with Cu²⁺ (40 mg/dm³), Zn²⁺ (5 mg/dm³), and Cr³⁺ (10 mg/dm³); c) Total biogas yield over 14 days of digestion recalculated per 1 gram of OM. Data are presented as mean ± SD of three independent experiments (n = 3). Statistical significance was evaluated using one-way ANOVA (p < 0.05).

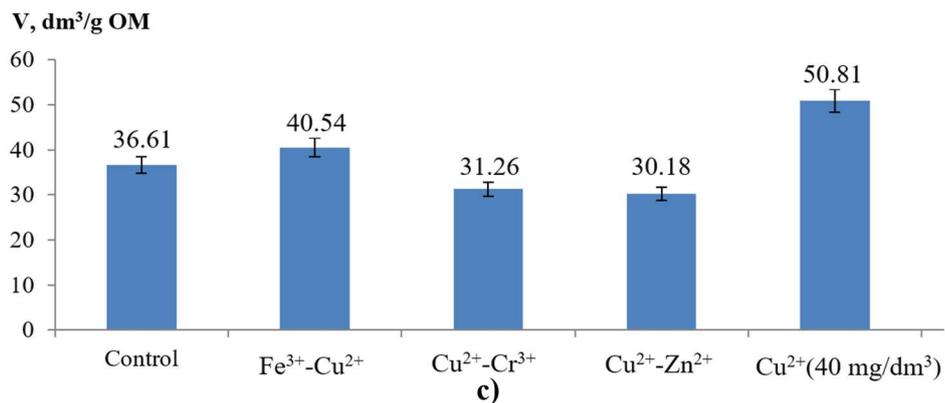
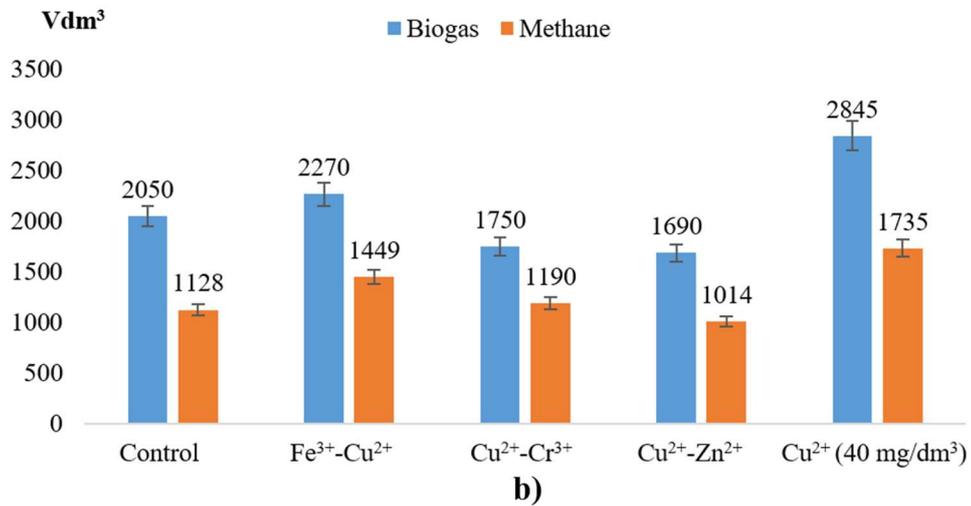
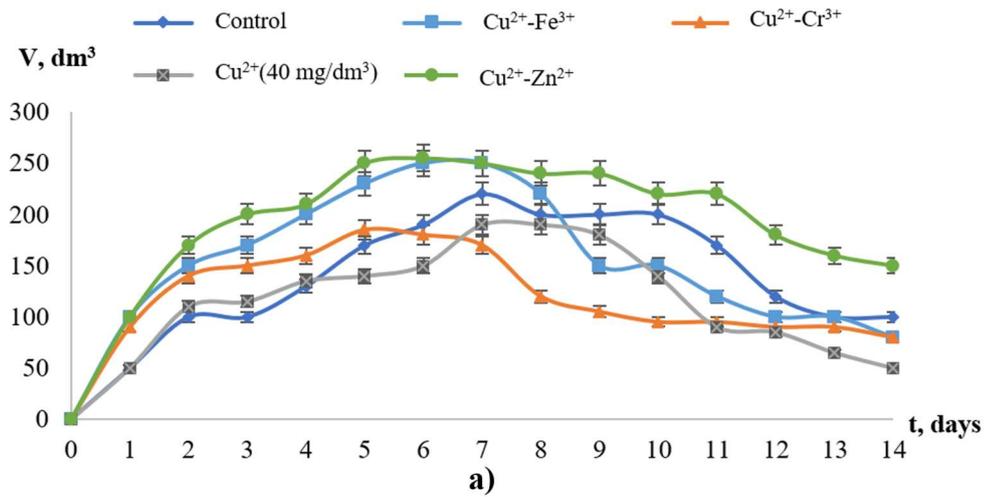


Figure 2. a) Daily biogas yield (V) under the combined effect of Cu²⁺ ions (40 mg/dm³) with Fe³⁺ (20 mg/dm³), Zn²⁺ (5 mg/dm³), and Cr³⁺ (10 mg/dm³); b) Total biogas (V) and methane (V) yield over 14 days of digestion under the combined effect of Cu²⁺ ions (40 mg/dm³) with Fe³⁺ (20 mg/dm³), Zn²⁺ (5 mg/dm³), and Cr³⁺ (10 mg/dm³); c) Total biogas yield over 14 days of digestion recalculated per 1 gram of OM. Data are presented as mean ± SD of three independent experiments (n = 3). Statistical significance was evaluated using one-way ANOVA (p < 0.05).

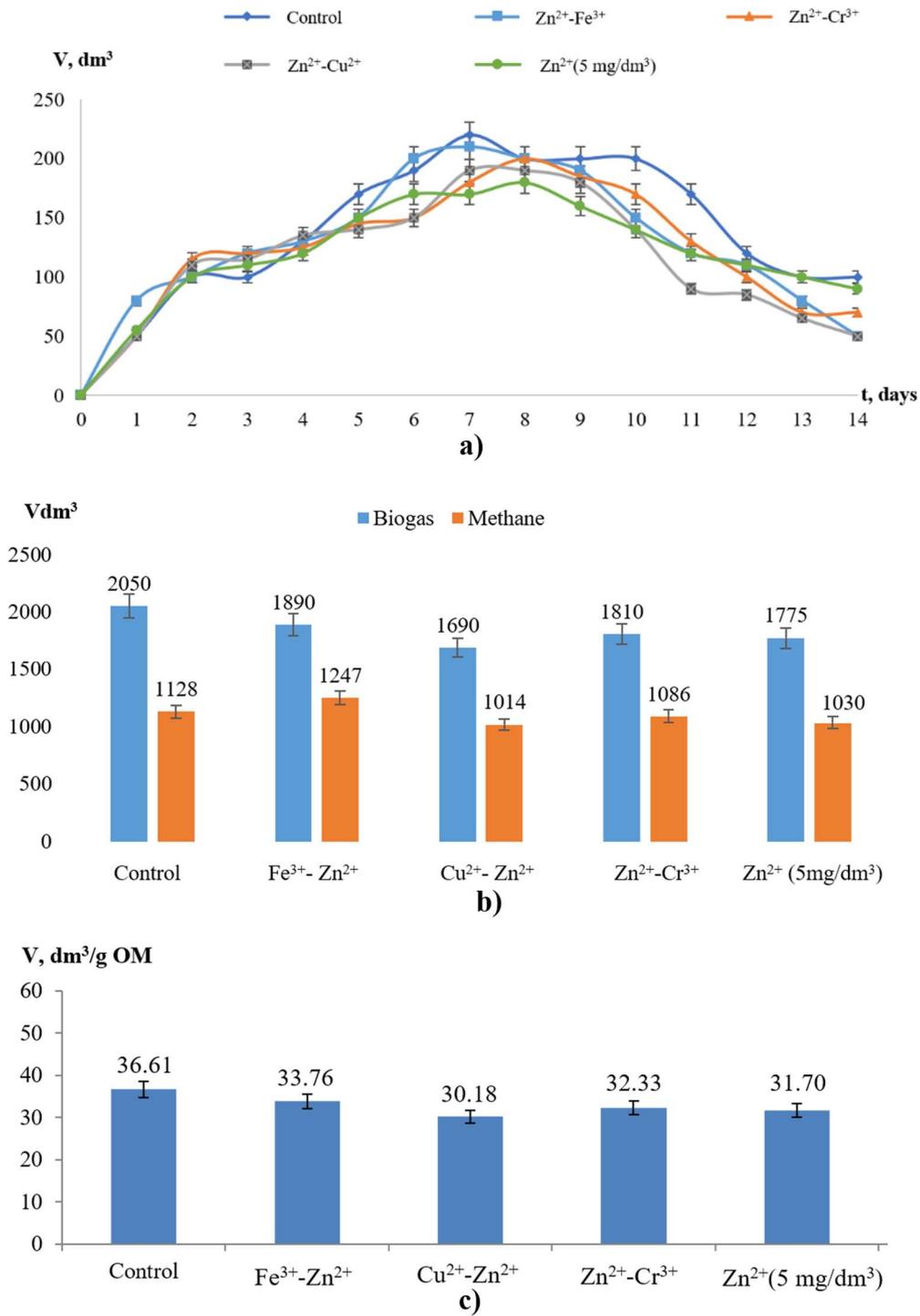
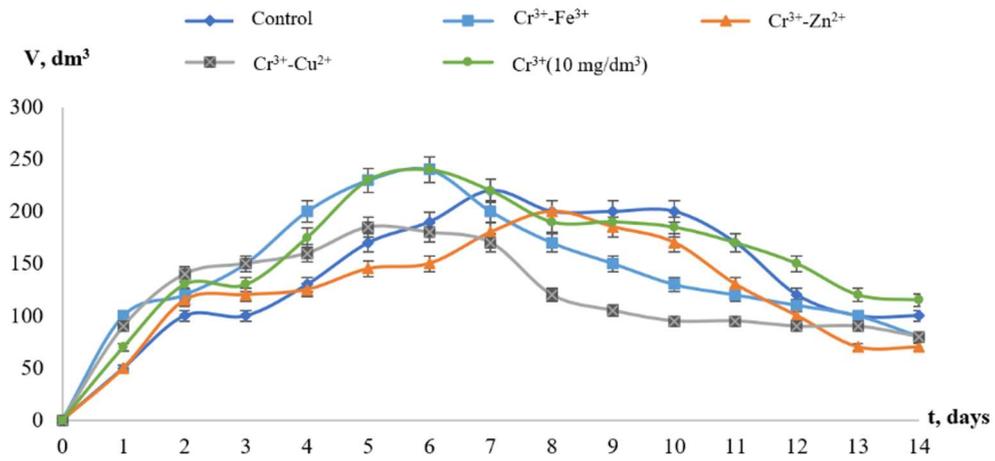
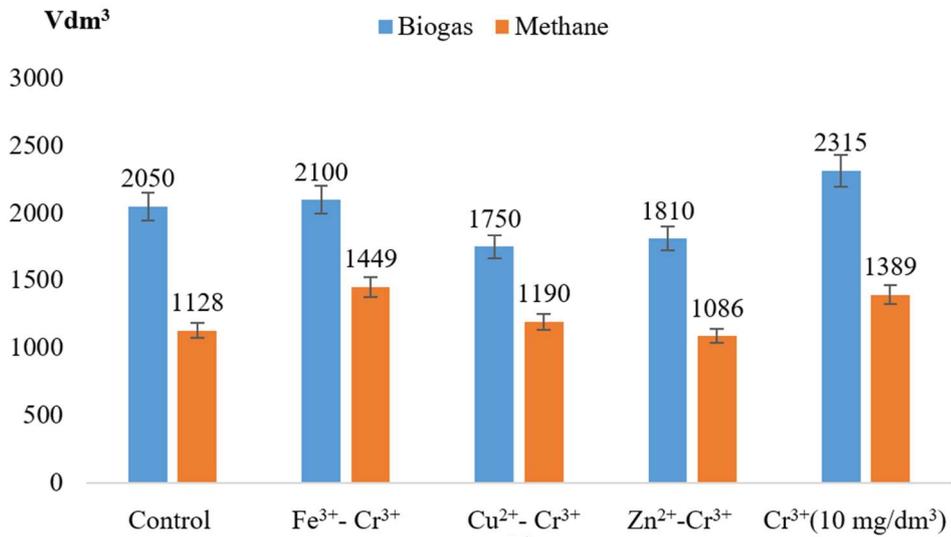


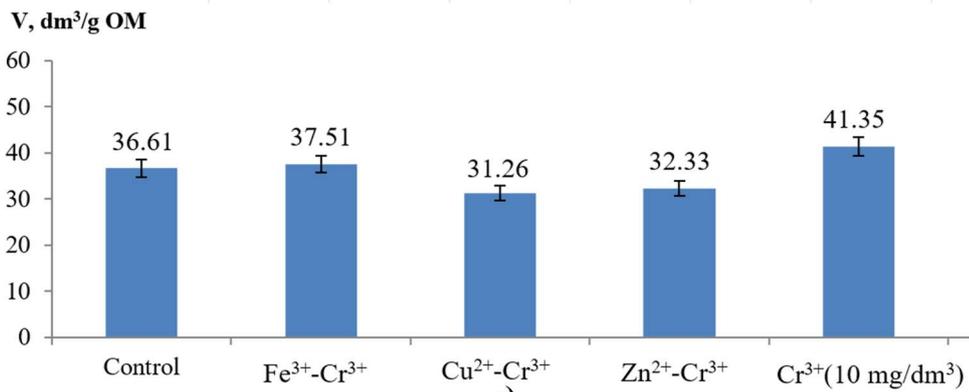
Figure 3. a) Daily biogas yield (V) under the combined effect of Zn²⁺ ions (5 mg/dm³) with Fe³⁺ (20 mg/dm³), Cu²⁺ (40 mg/dm³), and Cr³⁺ (10 mg/dm³); b) Total biogas (V) and methane (V) yield over 14 days of digestion under the combined effect of Zn²⁺ ions (5 mg/dm³) with Fe³⁺ (20 mg/dm³), Cu²⁺ (40 mg/dm³), and Cr³⁺ (10 mg/dm³); c) Total biogas yield over 14 days of digestion recalculated per 1 gram of OM. Data are presented as mean ± SD of three independent experiments (n = 3). Statistical significance was evaluated using one-way ANOVA (p < 0.05).



a)



b)



c)

Figure 4. a) Daily biogas yield (V) under the combined effect of Cr³⁺ ions (10 mg/dm³) with Fe³⁺ (20 mg/dm³), Cu²⁺ (40 mg/dm³), and Zn²⁺ (5 mg/dm³); b) Total biogas (V) and methane (V) yield over 14 days of digestion under the combined effect of Cr³⁺ ions (10 mg/dm³) with Fe³⁺ (20 mg/dm³), Cu²⁺ (40 mg/dm³), and Zn²⁺ (5 mg/dm³); c) Total biogas yield over 14 days of digestion recalculated per 1 gram of OM. Data are presented as mean ± SD of three independent experiments (n = 3). Statistical significance was evaluated using one-way ANOVA (p < 0.05).

The results of the research are indicated in a general schematic diagram (Fig. 5) that outlines the mechanisms of the combined action of heavy metals at the key stages of anaerobic digestion (hydrolysis, acidogenesis, methanogenesis).

No previous studies have reported on the combined effect of these concentrations of iron and copper. Compared with samples subjected to individual metal ions, it can be concluded that the combined effect is less efficient than the addition of a single metal. This may be due to the high concentrations of the compounds in the process, as doses of Cu^{2+} (~30–100 mg/L) were reported to increase cumulative biogas yield under conditions where copper was present without iron, suggesting that experiments with lower concentrations should be conducted [24]. Reference [17] reported increased NH_4^+ -N levels upon Cu (1 mg/L)–Fe (10 mg/L) addition (652.83 ± 61.88 mg/L) compared to the control with copper alone (1 mg/L) (476.63 ± 37.36 mg/L), which could have caused slight ammonia inhibition, potentially explaining the lower biogas yield relative to the single-metal sample.

Another study demonstrated the positive effect of Fe–Cu during the treatment of sewage sludge: the methane production rate increased by up to 34.4%, and the volatile solids (VS) removal rate reached 33.3% when treated with Fe–Cu microelectrolysis [18]. The oxidation of Fe^0 to $\text{Fe}^{2+}/\text{Fe}^{3+}$ and the reduction of Cu^{2+} to Cu^0 generate an electron flow, which partially breaks down complex organic polymers (lignin, cellulose, proteins), making the substrate more accessible to microorganisms. This process stimulates the enzymatic activity of hydrolytic enzymes (proteas-

es, glucosidases) and methanogenic enzymes (acetate kinase, coenzyme F_{420}).

The interaction of Fe^{3+} – Cr^{3+} ions resulted in a 13% increase in methane content compared to the control, although the total biogas yield increased by only 2.3%. Compared to the effect of individual metals, this combination showed a significantly lower biogas yield (23% higher for the iron sample (Fig. 1), and 9% higher for the chromium sample (Fig. 4)). However, it is notable that the methane content reached 62% for the combined metal treatment, compared to 59% for iron and 60% for chromium.

A study [25] on anaerobic digestion of chicken manure stimulated with a Fe–Cr–Co complex at low concentrations showed an increase in methane yield by 13.6% compared to the control, reaching 267.5 mL/g VSL at concentrations of Fe: 28.6 mg/L, Co: 16.2 mg/L, and Cr: 3.66 mg/L. This study demonstrated that the addition of trace elements Cr, Fe, and Co under anaerobic conditions in batch systems and laboratory scales successfully increased methane yield from the substrate; however, the individual effect of each metal ion was not examined.

It can also be concluded that iron ions positively influence biogas production at all stages, as confirmed by other authors [26, 27], while other metal ions primarily enhance the activity of methanogens, resulting in a significantly higher methane content in biogas compared to the control.

The Fe^{3+} – Zn^{2+} combination affects the fermentation process differently: due to the inhibitory effect of zinc on the first three stages of biogas formation (hydrolysis, acidogenesis, and acetogenesis), biogas production decreases by 8%, whereas during the final

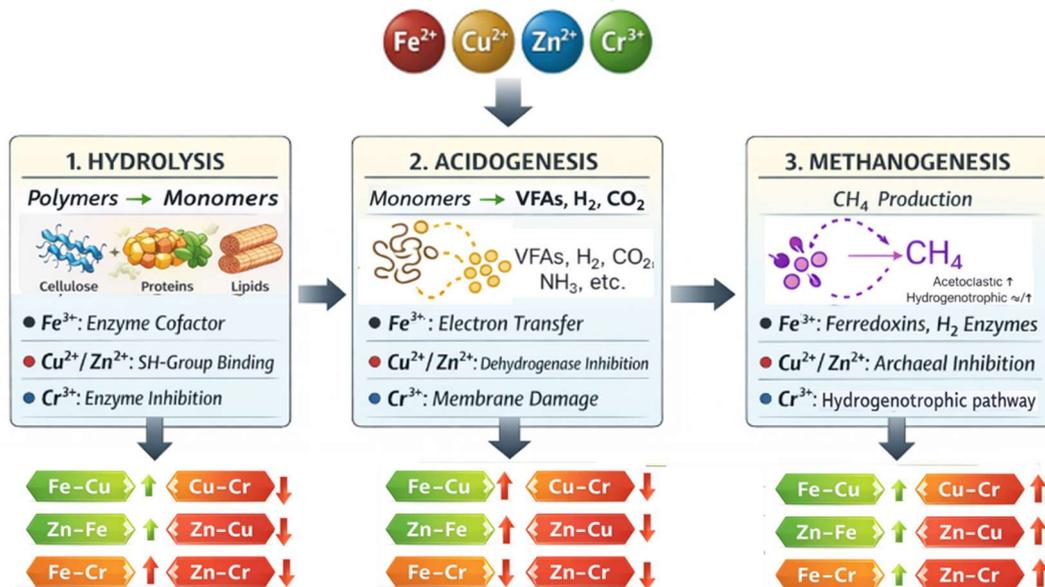


Figure 5. Conceptual diagram illustrating the combined effects of heavy metals on hydrolysis, acidogenesis, and methanogenesis during anaerobic digestion of cattle manure.

stage (methanogenesis), zinc exerts a positive effect, resulting in a 10.6% increase in methane content in the biogas. Furthermore, the literature reports a positive effect of iron nanoparticles at a concentration of 100 ppm, which increased biogas production by 180% and methane production by 234% [28]. This effect can be explained by the slow dissolution of Fe₂O₃ nanoparticles in the medium, which prevents aggressive impacts on microorganisms despite the high concentration. Zinc, in turn, plays an important role during methanogenesis by enhancing coenzyme M activity, so low concentrations of Zn²⁺ can support methanogenesis or process stability [29, 30], while higher concentrations lead to partial or complete inhibition. In the Fe–Zn combination, the inhibitory effect of high zinc concentrations is neutralized by the positive influence of iron, preventing inhibition of the anaerobic microbial activity and even increasing methane content in biogas from 57% to 66%. Compared to the effect of zinc alone (Fig. 3), the Fe–Zn combination shows a 6% higher biogas yield and a 17% higher methane yield, further confirming the positive role of iron on the anaerobic consortium exposed to zinc.

The combined effect of copper ions (Fig. 2) exhibits a slight positive effect when interacting with chromium: methane production increases by 5%, while overall biogas production decreases by 15%. In the Cu²⁺–Zn²⁺ combination, the inhibitory effect on biogas formation is more pronounced, with biogas production decreasing by 17.6%. Nonetheless, a slight stimulatory effect of copper combined with other metals on methane production is also observed. The positive combined effect of Cu²⁺–Cr³⁺ has been investigated in [31], showing that lower concentrations of Cu (1.82 µg/g DM) and Cr (0.89 µg/g DM) act as microelements for the anaerobic microbial consortium, stimulating biogas production and methanogenesis. Study [32] indicates that Cr³⁺ can be tolerated up to ~50 mg/L, and Cu²⁺ up to ~40 mg/L in the context of their combined effect.

The negative impact of the combination of bulk and nanosized CuO and ZnO particles on biogas and methane production during anaerobic digestion of cattle manure is confirmed by study [33]. Other authors also concluded that Cu- and Zn-based nanoparticles exhibit a material inhibitory effect that intensifies over time, confirming the toxicity of nanoparticles due to the release of metals during anaerobic digestion [34].

The stimulatory and inhibitory effects of Cu ions on anaerobic fermentation remain controversial, as whether heavy metals act as stimulators or inhibitors for anaerobic microorganisms depends on the overall metal concentration, chemical forms of the metals, and process-related factors such as pH and redox potential. For instance, the addition of Cu²⁺ has been reported to enhance the hydrolysis of lignin and hemicellulose and the degradation of organic molecules that do

not contain volatile fatty acids, thereby promoting biogas production [35]. Certain methanogens, through their enzymes, exhibit a stimulatory response to Cu²⁺ (e.g., acetyl-CoM synthase, superoxide dismutase (SOD), ammonium monooxygenase, etc.) [36].

The effect of the Cu²⁺–Zn²⁺ combination on the microbial composition across the three stages of anaerobic fermentation (hydrolysis, acidogenesis/acetogenesis, methanogenesis) was studied in [19, 37], which explains the inhibitory action of this combination: Cu²⁺ strongly inhibits *Hydrogenispora* (hydrolysis), *SBR1031* and *Ruminofilibacter* (acidogenesis/acetogenesis), responsible for the breakdown of complex organic compounds, whereas Zn²⁺, conversely, promotes the growth of *SBR1031* during hydrolysis and *C10-SB1A* during acidogenesis – this microbial group likely participates in hydrolysis or the degradation of high-molecular-weight substrates [28]. During methanogenesis, the addition of Cu or Zn enhances microbial activity, indicating that both metals exert a positive effect on methanoarchaea or the methane production stage.

The combined effect of chromium (III) and zinc (II) ions on biogas yield also exhibits an inhibitory effect: biogas production decreased by 11.7% compared to the control, although the effect of chromium alone resulted in a much higher biogas yield – 22% higher than the combined effect of the two metals and 11.4% higher than the control. Studies on the combined effect of chromium and zinc in the literature are lacking; therefore, the assessment can be made based on the influence of individual ions on biogas production [13, 38]. Both zinc and chromium act as cofactors for enzymes at low concentrations, but at higher concentrations, they reduce enzyme activity and may inhibit protein synthesis in hydrolytic and acetogenic bacteria. This has a negative effect on the initial stages of biogas formation. However, at the concentrations used in this study, stabilization of pH and redox potential occurs, which does not halt the process and even increases methane content in the biogas. This effect is likely mediated by *Methanobacterium* spp. and *Methanobrevibacter* spp. (hydrogenotrophic methanogens) or *Methanosarcina* spp. and *Methanosaeta* spp. (acetotrophic methanogens). Considering that Cr³⁺ participates in the stabilization of dehydrogenase, reductase, and certain acetogenic enzymes, facilitating the more efficient conversion of acetate and hydrogen with CO₂ into biomethane, it is probable that chromium exerts a positive effect specifically on hydrogenotrophic methanogens.

Research limitations

Despite the valuable findings obtained from the study, several limitations should be acknowledged

Limitations of the batch system and extrapolation to industrial scale: The batch reactors used in the experiment do not fully replicate the continuous anaerobic digesters used in industrial biogas and biomethane production, where substrate heterogeneity and operational fluctuations may also affect the results. Therefore, it can be expected that the dynamics of metal ions and the adaptation of microorganisms of the anaerobic association may differ under industrial conditions.

Anaerobic association analysis of microorganisms: The study focused on the process outputs, which are the products of the vital activity of microorganisms (biogas and methane), but did not consider investigating the detailed characterization of the microorganisms of the population exposed to the combined action of metal ions, which is the goal of further research by the authors.

Limited metal concentrations: Only certain doses of metal ions were tested those that in previous studies gave a positive effect on biogas and biomethane yield. Lower or intermediate concentrations may have different effects.

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Conclusions

An increased concentration of any metal ion (except zinc) leads to an increase in biogas yield compared to the combined action of multiple metals. Under the simultaneous action of Fe³⁺-Cu²⁺, biogas yield increased by 9.7%, and Fe³⁺-Cr³⁺ by 2.3% relative to the control. At the same time, the methane content in biogas increased by 22% and 13%, respectively.

The interaction of other combinations of the studied heavy metals exhibits an inhibitory effect on biogas yield, but enhances methane content in the biogas: Fe³⁺-Zn²⁺ by 10.6%, and Cr³⁺-Zn²⁺ by 3.4%.

It was established that copper, chromium, and zinc ions have an inhibitory effect during the first three stages of biogas formation, while exerting a stimulating effect on methanogenesis.

Interests disclosure

The authors declare no conflicts of interest.

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КОМБІНОВАНИЙ ВПЛИВ ІОНІВ ВАЖКИХ МЕТАЛІВ ($\text{Fe}^{3+}\text{-Cu}^{2+}$, $\text{Fe}^{3+}\text{-Zn}^{2+}$, $\text{Fe}^{3+}\text{-Cr}^{3+}$, $\text{Cu}^{2+}\text{-Zn}^{2+}$, $\text{Cu}^{2+}\text{-Cr}^{3+}$ та $\text{Zn}^{2+}\text{-Cr}^{3+}$) НА ПРОДУКТИВНІСТЬ ВИРОБНИЦТВА БІОГАЗУ ТА БІОМЕТАНУ

Вступ. З'ясування впливу дії комбінації металів на анаеробну асоціацію мікроорганізмів у процесі зброджування та продукування біометану.

Мета. Дослідити вплив одночасної взаємодії іонів важких металів (Zn-Fe, Zn-Cu, Zn-Cr, Fe-Cu, Fe-Cr, Cu-Cr) на процес виробництва біогазу та утворення біометану в ньому.

Методи. Лабораторне дослідження в умовах, наближених до промислового виробництва, із застосуванням впливу солей іонів важких металів з вимірюванням кількості та якісного вмісту кінцевого продукту.

Результати. Комбінований вплив двох іонів важких металів на продукування біогазу анаеробною асоціацією мікроорганізмів є специфічним: синергія деяких іонів металів можуть стимулювати біосинтез біометану, але пригнічувати продукування біогазу. Зокрема Fe (20 мг/дм³) - Cu (40 мг/дм³) та Fe (20 мг/дм³) - Cr (10 мг/дм³) мають незначний позитивний вплив на вихід біогазу порівняно з контролем, а взаємодія з цих іонів металів з Zn (5 мг/дм³) зменшує вихід біогазу, але покращує якісний його склад - вміст біометану підвищується.

Висновки. Комбінований вплив 2-х іонів важких металів в загальному зменшує виробництво біогазу порівняно з контролем, однак стимулює продукування більшого вмісту біометану у біогазі. Порівняно з впливом дії одного важкого металу, комбінований вплив немає позитивного ефекту на процес виробництва біогазу, що зумовлено завищеними концентраціями іонів металів, що використовувалися в досліді.

Ключові слова: важкі метали; Залізо; Цинк; Мідь; Хром; біогаз; біометан.