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Evaluation of additive effect on anaerobic sewage sludge digestion

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Abstract: An additive based on iron oxides was applied to reduce the amount of produced sludge and to increase the production and quality of biogas. The C/N ratio was 11.0–11.3 and the pH of the sludge mixture was 7.3 before the anaerobic digestion. The determined optimal dose of the additive was 0.35 g/g of sludge dry matter over 20 days. This allowed a reduction in the sludge retention time up to 6–11 days. Consequently, maximum biogas production was reached on average 1.6 times faster, volatile solids degradation increased by 56.7%, biogas production increased by 75%, specific biogas production increased by 11.5%, and methane concentration in the biogas increased by 8.4%–18.2%. When the additive was applied, the quantity of phosphate phosphorus in the supernatant was reduced by up to 19%, and hydrogen sulfide reduction efficiency in the biogas ranged between 55% and 62%. In sludge treatment facilities, using an iron oxide-based additive could reduce the dewatering and drying costs for digested sludge by up to 35% .

Introduction

Waste generation is an essential feature of human activity, but its disposal has become a significant problem for all societies and economies (Górka and Cimochowicz-Rybicka 2019). Sewage sludge treatment is still a problem, as it has yet to be satisfactorily resolved in terms of cost and final disposal (Suschka and Grübel 2017). The amount and quality of sewage sludge produced are closely related to wastewater treatment innovations and the degree of wastewater treatment (Buta et al. 2021). Large amounts of sludge have already become an environmental problem, but using the most advanced technology could reduce the harmful impact of sewage sludge on the environment (Ye et al. 2022). Sewage sludge may contain a wide range of contaminants, including toxic substances such as metals, persistent organic pollutants (POPs) and pathogens (Yesil and Tugtas 2019; Hoang et al. 2022).

Treatment of sewage sludge involves a variety of processes, including incineration, composting, and anaerobic digestion (Kim et al. 2003; Meng et al. 2021). Incineration can reduce sewage sludge volume by up to 90 % and destroy toxic organic compounds (Liew et al. 2021). On the other hand, due to its carbon and nutrient content, sludge can also enhance soil fertility (Lamastra et al. 2018). High temperature aerobic composting is an effective method to reduce sludge dry matter content and mitigate its harmfulness, but the composting process emits pollutants and can lead to a 40–80 % nitrogen loss due to ammonia emissions (Meng et al. 2021). Anaerobic digestion is regarded as the most effective method for sewage sludge management (Jain et al. 2015; Berenjkar et al. 2018; Filer et al. 2019). While anaerobic digestion technologies have become widespread in recent decades, the process is relatively long-term (15–30 days), and only part of the organic matter (30–50 %) is converted to biogas (Kim et al. 2003; Jain et al. 2015; Tyagi and Lo 2011). Strategies and measures to reduce sludge volume, increase biogas yield, and improve biogas quality are actively being pursued, though they often require substantial capital and operational costs (Bizimana et al. 2021; Nghiem et al. 2014; Vongvichiankul et al. 2017; Wang et al. 2020).

Among sewage sludge pre-treatment methods are ultrasound and high-voltage disintegration (Kim et al. 2003; Dauknys et al. 2020), and the application of chemical reagents (Reddy et al. 2017). Iron or aluminum salts can bind phosphorus or reduce hydrogen sulfide but may also disrupt the digestion process (Smith et al. 2009). Overuse of metal salts accelerates the growth of acid-producing bacteria, disturbing the balance between acidogens and methanogens (Latif et al. 2017). Moreover, excessive metal salts may lead to a shortage of phosphorus, essential for microbial activity. Iron oxide additives have been used to enhance sludge digestion processes, resulting in greater biogas production and higher methane concentration (Lee and Shoda 2008; Hao et al. 2017; Agani et al. 2017). In addition, trivalent iron additives remove nitrogen from the sludge during anaerobic digestion (Yang et al. 2018), and waste iron scrap can bind the phosphate (Zheng et al. 2013). The application of waste iron powder also decreases hydrogen sulfide content in biogas (Andriamanohiarisoamanana et al. 2018). Thus, the addition of iron oxides and hydroxides to the digestion process accelerates microbial growth and can expand microorganism species diversity (Xiao et al. 2018). Interactions among different microbial species can improve the effectiveness of anaerobic digestion (Cheng et al. 2020).

The exact effect of iron oxides on assimilation remains undetermined, and the assimilation process using iron oxides has not been fully characterized. The biogas generated through anaerobic digestion is considered as a multifunctional renewable resource and could serve as a promising alternative to depleting traditional fuels (Szaja and Bartkowska 2024).

The aim of this study was to examine the impact of an additive containing bivalent and trivalent iron oxides on the anaerobic digestion of sewage sludge. A detailed analysis of the digestion results with this additive provides valuable insights for future studies on the effects of iron oxides in the anaerobic sludge digestion process.

Materials and Methods

Source of investigated sludge

A mixture of primary and excess sludge, collected before the digestion process, and inoculum sludge from the digester were taken from the sludge treatment facilities at the Silute Wastewater Treatment Plant (WWTP) for this study. The inoculum was needed to initiate the digestion process as quickly as possible under laboratory conditions. The designed capacity of the sludge treatment plant is 1,333 kg of dry mass (DM) per day. The Silute WWTP has sludge treatment facilities that receive and anaerobically stabilize primary sludge and excess activated sludge, as well as excess sludge from smaller WWTPs. The wastewater treatment process generates an average of 490 kg DM/day of primary sludge and 1,560 kg DM/day of excess sludge, for a total of 2,050 kg DM/day.

After thickening the sludge in gravity thickeners, the thickened sludge is fed into a sludge mix tank at a total flow rate of 48.0 m^3/day. This tank supplies an average of 1,160 kg of sludge per day into a digester with a volume of 650 m^3. Thus, only part of the excess sludge is supplied, as foreseen in the project. To increase the amount of sludge digested and enhance the amount and quality of biogas produced, this study investigates the effect of reactants on the digestion process. The actual average specific biogas production is 0.88 N m^3/VS destroyed. The mixture of primary and excess sludge, collected from the line between the sludge mix tank and the heat exchanger before the digestion process, and the sample from the recirculating sludge digestion line were used for this study.

Laboratory installation of anaerobic digestion

A laboratory test was performed at VILNIUS TECH using anaerobic digestion model "W8 Armfield Ltd" (UK). The setup consisted of two anaerobic reactors operating in parallel, each with a working volume of 4.6 liters. A constant temperature of 37° C was maintained in each reactor using an electric heating mat. The sludge was kept in suspension by a mechanical stirrer rotating at 80 rpm. The selected sludge retention time was 20 days. The produced biogas was measured using the water relocation strategy and collected in calibrated vessels with a volume of 2000 ml volume, connected to each reactor.

Table 1. Composition of additive.

Substances	**Quantity, %**
Fe_2O_3	47.39
FeO	38.99
Fe (metal)	0.71
C	4.6
SiO_2	1.29
MnO	0.82
CaO	0.54
Al_2O_3	0.43
MgO	0.42
Humidity 550 °C	3.71
Cr_2O_3, V_2O_3, TiO_2, K_2O, P_2O_5, ZnO, CoO, NiO, CuO, As_2O_3, MoO	0.76
Na_2O, BaO, PbO, CdO, SnO, WO_3, Cl, SeO, Sb_2O_3	0.34
Total	100

Additive

An iron oxides-based additive was used in the research. This additive is a black and dark brown powder, insoluble in water and non-flammable, with a density of 2.25 g/cm^3. The composition of the additive is presented in Table 1.

As shown in Table 1, the additive has the highest content of Fe_2O_3 (> 47%), followed by FeO (> 38%). The remaining part of the additive consists of carbon, moisture, and other metal oxides, each comprising more than 1% of the total weight.

Procedure of tests

The research was performed in two stages. At the beginning of each stage, dry mass (DM) and volatile solids (VS) were determined for both the sludge mixture and in the inoculum. Based on the determined VS values, the sludge mixture and inoculum were mixed at a ratio of 5:1. The required amount of inoculum was calculated using the following equation, as provided by the authors (Dauknys et al. 2020):

$$V_P = \frac{VS_T \cdot 4{,}6}{5 \cdot VS_P + VS_T}\ , L \qquad (1)$$

Where:

V_P – required volume of inoculum (l);

VS_T – concentration of VS in sludge mixture before digestion (g VS/l);

VS_p – concentration of VS in the inoculum (g VS/l);
4,6 – volume of the anaerobic reactor (l);
5 – ratio between VS parts of sludge mixture to be digested and the inoculum.

After mixing the calculated amount of inoculum with the primary and excess sludge mixture, the concentrations of DM and VS in the resulting mixture were determined again. This mixture was then used to fill two anaerobic reactors. An appropriate dose of the iron-based additive was added to bind phosphate phosphorus and remove hydrogen sulfide (as described by equations (2) and (3)). The parameters required to calculate the preliminary demand for the additive were based on actual data from the Silute WWTP. The additive dose was then adjusted according to the volume of the anaerobic reactors.

The demand of the additive to bind phosphate phosphorus was calculated using the following equation drawn up based on ATV-DVWK (ATW-DVWK 2000):

$$m_{additive,\ P} = \frac{V_{sludge} \cdot \Delta\mathrm{P} \cdot m_{Fe} \cdot R_{Fe}}{1000}, g \tag{2}$$

Where:
$m_{additive,\ P}$ – demand of the additive to bind phosphate phosphorus (g);
V_{sludge} – sludge volume (m^3);
ΔP – the concentration of phosphates to be removed from the supernatant (g P/m^3);
m_{Fe} – demand of iron to bind phosphate phosphorus (g Fe/g P);
R_{Fe} – amount of iron in the additive (%).

The demand of the additive to remove hydrogen sulfide was calculated using the following equation, drawn up based on Polster and Brummack (Polster and Brummack 2009):

$$m_{additive,\ H2S} = R_{Fe} \cdot \frac{\left(\beta \cdot \frac{M_{Fe}}{M_s} \cdot \left(\frac{H_2S_{(aq)}}{f_{H_2S}} \cdot V_{sludge} + \frac{\Delta H_2S_{(g)}}{1000}\right) \cdot \rho_{H_2S} \cdot V_{biogas}\right)}{100}, g \tag{3}$$

Where:
$m_{additive,\ H_2S}$ – demand of the additive to remove hydrogen sulphide (g);
β – overdose factor;
M_{Fe} – molecular weight of iron (g/mol);
M_S – molecular weight of sulphur (g/mol);
$H_2S_{(aq)}$ – concentration of soluble hydrogen sulphide (g/m^3);
f_{H2S} – the sulphur fraction in soluble hydrogen sulphide (%);
V_{sludge} – volume of sludge (m^3);
ΔH_2S – amount of hydrogen sulphide to be removed from biogas (ppm);
ρ_{H2S} – density of hydrogen sulphide (g/l);
V_{biogas} – volume of biogas (m^3);
R_{Fe} – amount of iron in the additive (%).

The calculated dose of the additive was added to the digested sludge mixture with inoculum before the start of the digestion process, i. e., the required amount of additive for 20 days was added. In the second stage of the research, the dose of the additive was reduced by 0.1 g/g DM/20 day. The selected doses of the additive at different stages of the digestion process are presented in Table 2.

The concentrations of DM and VS were also determined in the digested sludge of each reactor after 20 days. In addition, before and after digestion, phosphate phosphorus and soluble

Table 2. Doses of sludge at individual stages of the research.

Parameter	**Stage I**	**Stage II**
Applied a single dose of additive to the digestion process for 20 days, g/g DM of sludge mixture	0.45	0.35
Relative daily dose of additive, g/kg DM	22.5	17.5

Table 3. Sludge mixture quality before the digestion process (values of arithmetical average).

Parameter	**Stage I**	**Stage II**	**Difference, %**
Soluble COD in supernatant, mg O_2/l	1495	1681	11
NH_4^+–N in supernatant, mg/l	245	266	7.9
Soluble COD/ NH_4+–N in supernatant, mg/l	6.1	6.3	3.2
pH	7.3	7.3	0.0
C/N	11.0	11.3	2.7
DM in sludge mixture, g DM/l	31.0	28.9	6.8
VS in sludge mixture, g VS/l	22.1	20.7	6.3
Percentage of primary sludge in sludge mixture, %	24	29	17
Percentage of excess sludge in sludge mixture, %	76	71	6.6

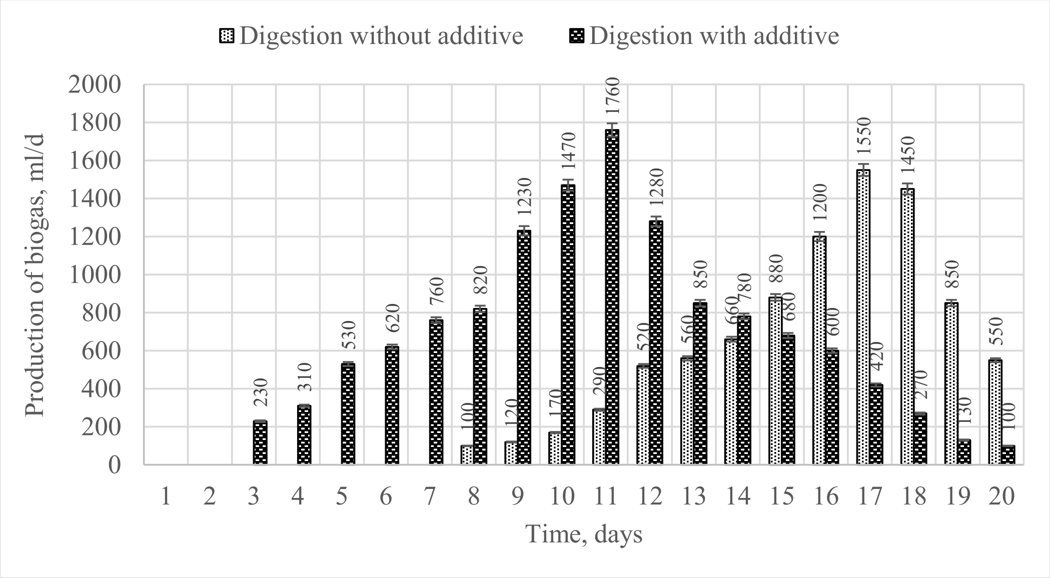

Figure 1. Biogas production process in Stage I.

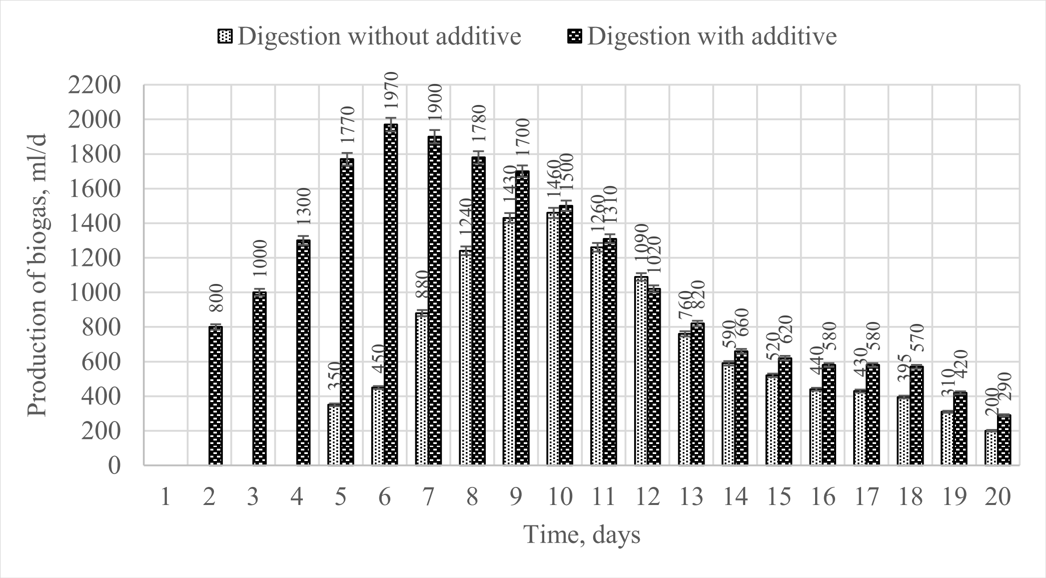

Figure 2. Biogas production process in Stage II.

chemical oxygen demand (COD) were measured in the supernatant. The parameter values were analyzed 3 times for each test.

The daily amount of biogas produced was recorded, and the concentrations of methane and hydrogen sulfide in the biogas were measured daily.

Analysis methods

Sampling was conducted according to standards ISO 5667–13:2011, ISO 5667–1:2006, ISO 5667–10:2011. The concentration of DM was determined according to EN 15934:2012, and the concentration of VS was determined according to EN 12880:2002. Phosphate phosphorus concentration was measured based on ISO 6878:2004, and chemical oxygen demand was determined according to ISO 6060:2003. The biogas composition was analyzed using a GasData series GFM410 gas composition analyzer. Measurement accuracy for CH_4 was 0.2 % @ 5 %, 1.0 % @ 30 %, 3.0 % @ 100 %, with a range of 0–100 %. Measurement accuracy for H_2S was 5% of full scale (fs), with a range up to 1500 ppm. The experiment was repeated 3 times, and the average values were calculated. Selected data were processed statistically using an outlier test, with a 95% confidence interval. The data collected were analyzed using STATGRAPHICS (2018).

Results and discussion

The characteristics of the primary and excess sludge mixture with the inoculum before the digestion process are presented in Table 3.

As shown in Table 3, the C/N ratio in the sludge mixture during stages I and II was similar and close to eleven. The digestion performance of the initial feedstock could be reflected by the C/N ratio, making it a key indicator of the initial feedstock's quality (Li et al. 2024). Generally, a higher

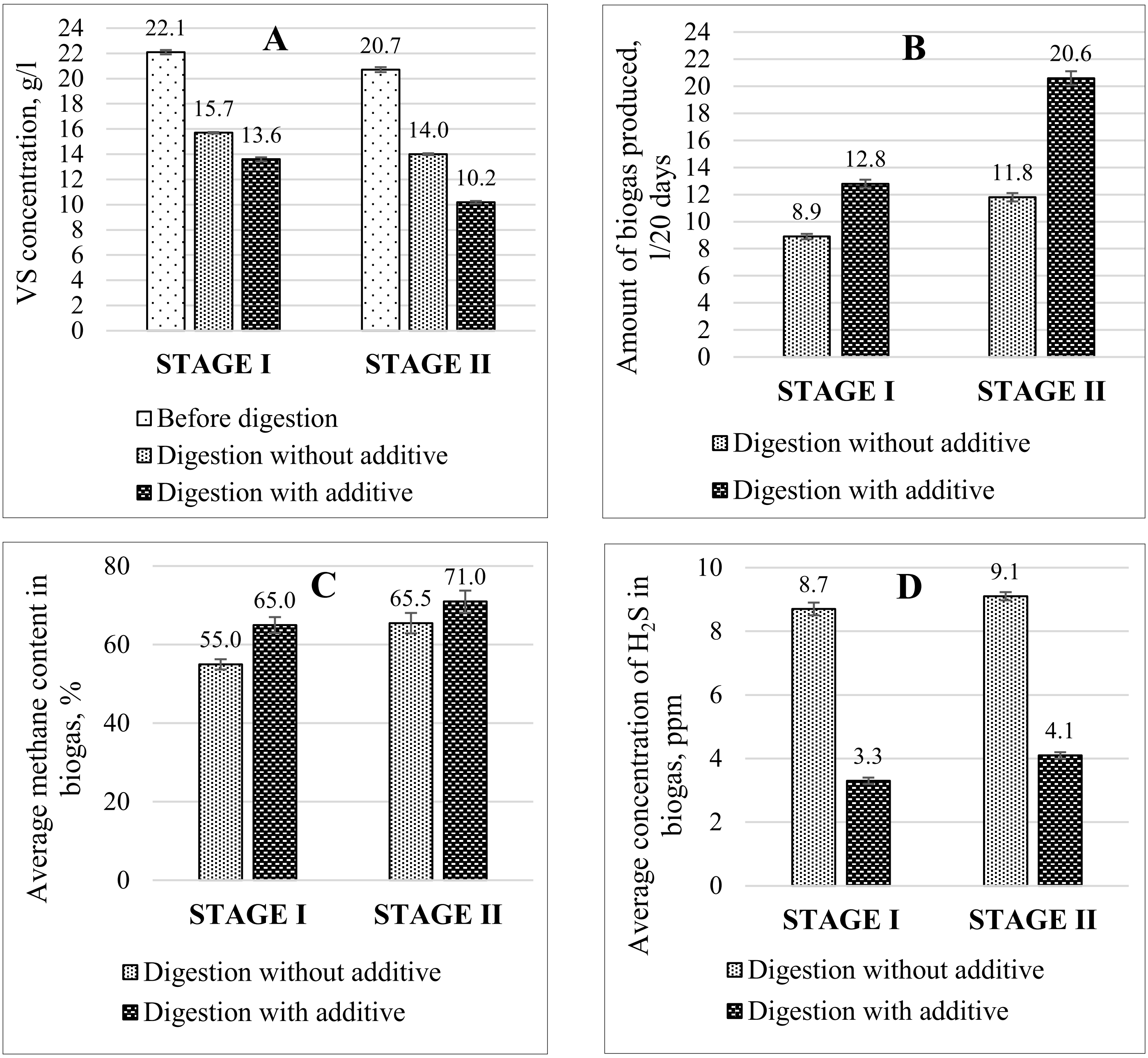

Figure 3. VS concentration (A), amount of biogas produced (B), methane concentration in biogas (C) and hydrogen sulphide in biogas (D).

C/N ratio results in a more stable pH and better methanogenic activity due to the enhanced buffering effect of the digestion medium. According to Hallaji et al. (2019), the optimal C/N ratio for the anaerobic decomposition of organic matter is approximately 20-30. Organic wastes vary in their C/N ratios, for example, the C/N ratio is 24 for cow manure, 11–19 for vegetable waste, 55 for cassava peel, 36 for yam peel, 40–46 for sweet potato peel, 24–30 for bean waste, 90–130 for rice waste, 2.5–5.5 for fish waste, 30–37 for plantain waste, 20–50 for fruit waste, and 19 for sheep dung (Orhorhoro et al. 2016).

Table 4. Volatile solids mass balance (g of VS).

Stage	I			II		
	Before digestion	After digestion	Degradation	Before digestion	After digestion	Degradation
Digestion without additive	102	72	30	95	64	31
Digestion with additive		63	39		47	48

It can be concluded that the C/N ratio of the sewage sludge mixture used in this study is relatively low, which could have negatively affected the activity of methanogenic bacteria.

The data presented in Table 3 show that the quality of the sludge mixtures used in Stages I and II differed by 6–17 % based on individual parameters. The largest differences were observed in the percentage of the primary sludge (17%) and the concentration of soluble COD (11%). The higher concentration of soluble COD in Stage II is attributed to the higher percentage of primary sludge in the sludge mixture. Primary sludge is the main source of COD; only 26% and 7% of the total COD from primary and secondary sludge, respectively, can be converted to methane through anaerobic digestion (Wan et al. 2016). During biological wastewater treatment, soluble COD is first converted into biomass, from which energy is subsequently recovered through anaerobic digestion, albeit with low energy efficiency (Rossle and Pretorius 2001). The biogas production process is presented in Figures 1 and 2.

Comparing the results of the two stages when the sludge was digested with the additive, it was observed that the digestion process started 1 day earlier, and the peak of biogas production was reached 5 days earlier in Stage II (Figures 1 and 2). Furthermore, biogas production in Stage II was 60 % higher than in Stage I. Thus, using a higher dose of the additive did not yield better results. However, the use of the additive may still be a variable solution to intensify the digestion process, shorten sludge retention time (SRT), increase biogas production, and enhance energy generation potential. In this study, SRT was equal to hydraulic retention time (HRT) as it was a batch test. The use of the additive led to 3 main observations: (1) the onset of biogas production occurred 3–5 days earlier; (2) the peak of biogas production was reached 4–6 days earlier relative to the onset of biogas production; and (3) biogas production increased by 44–74% compared to sludge digestion without the additive. The results show that an SRT of 6–11 days is sufficient to achieve and maintain efficient biogas production with the additive, while the SRT was 10–17 days without the additive (Figures 1 and 2).

The impact of the additive on the VS concentration, biogas production, and biogas quality is presented in Figure 3, while the VS mass balance is presented in Table 4.

As shown in Figure 3, the total increase in biogas production was observed after the addition of the additive. Iron typically contains various key methanogenic enzymes and co-enzymes. Additionally, iron acts as an electron donor, enhancing overall hydrogen uptake when supplemented in anaerobic digesters (Fraghali et al. 2020). Divalent or trivalent iron can react with H_2S to form iron sulfide (FeS), which precipitates and thus prevents the release of hydrogen sulfide (Ruan et al. 2017).

It was determined that the degradation of VS increased by 32.8 % in Stage I when the sludge was digested with the additive, while the degradation of VS increased by 56.7 % in Stage II. This indicates that the use of the additive has a positive effect on the sludge digestion process. The obtained results are within the range reported by other authors. For example, Cheng et al. (2020) found that the addition of iron compounds to the digestion process can increase VS destruction by up to 36.2 %.

The use of the additive resulted in a VS degradation efficiency of 38.5 % in Stage I and 50.7 % in Stage II. Comparing the difference in VS degradation efficiency with and without the additive for each stage, it was found that the improvement in VS degradation efficiency was 1.9 times higher in Stage II than in Stage I. It is assumed that the dose of the additive used in Stage I may have been too high, leading to suboptimal digestion. This assumption is supported by the research of Al Mamun and Torii (2015), who found excessive amounts of iron compounds can inhibit the digestion process. In addition, the higher VS degradation efficiency in Stage II may have been affected by the higher proportion of primary sludge in the sludge mixture (Table 3).

Biogas production increased by 43.8 % in Stage I when the sludge was digested with the additive, while in Stage II, biogas production increased by 74.6 %. It has been reported that the addition of iron oxide powder to the digestion process can increase biogas production by up to 62 % (Agani et al. 2017).

Specific biogas production increased by 8.6 % in Stage I and by 11.5 % in Stage II due to the use of the additive. According to Hao et al. (2017), the use of waste iron scraps during anaerobic digestion resulted in a 21.4% increase in methane production. The results obtained in this study show that the addition of the iron oxides-based additive to the digestion process had a positive effect on biogas production in both stages. It is concluded that the use of the additive dose of 17.5 g/kg DM can increase the biogas production by up to 75 %.

Figure 3 (C) shows that the methane concentration in biogas was lower in Stage I. This result can be explained by the fact that in Stage I, the percentage of primary sludge in the digested sludge mixture was 17 % lower than in Stage II (Table 2). As is known, organic matter in primary sludge is more readily available to the microorganisms involved in the digestion process. The average methane concentration increased by 18.2 % in Stage I when the sludge was digested with the additive, while in Stage II, the methane concentration increased by 8.4 %. In this case, the methane concentration in the biogas increased to 71%. Thus, it can be assumed that the additive has a greater effect on increasing methane concentration in biogas when the percentage of primary sludge in the digested sludge mixture is lower (24%).

Figure 3 (D) shows that the concentration of hydrogen sulfide in the biogas decreased when the additive was used in the digestion process. The reduction in hydrogen sulfide concentration was 62 % in Stage I when the sludge was digested with the additive, while the reduction efficiency was 55 % in Stage II. It can be stated that reduction in hydrogen sulfide concentration in biogas is more effective with the addition of a higher dose of the additive. According to other authors (Andriamanohiarisoamanana et al. 2018), the concentrations of hydrogen sulfide in biogas could be reduced by up to 93 % due to the use of iron oxide powder.

The impact of the additive on the parameters of supernatant is presented in Figure 4.

Figure 4 (A) shows that the concentration of phosphate phosphorus in the supernatant after 20 days of digestion increased by 4.6 % in Stage I and by 8.6 % in Stage II when the sludge was digested without the additive. In contrast, when the additive was used, the concentration of phosphate phosphorus in the supernatant decreased by 19 % in Stage I and by 14 % in Stage II compared to when the additive was not used. The greater reduction of phosphate phosphorus in Stage I can be attributed to the higher dose of the additive used in

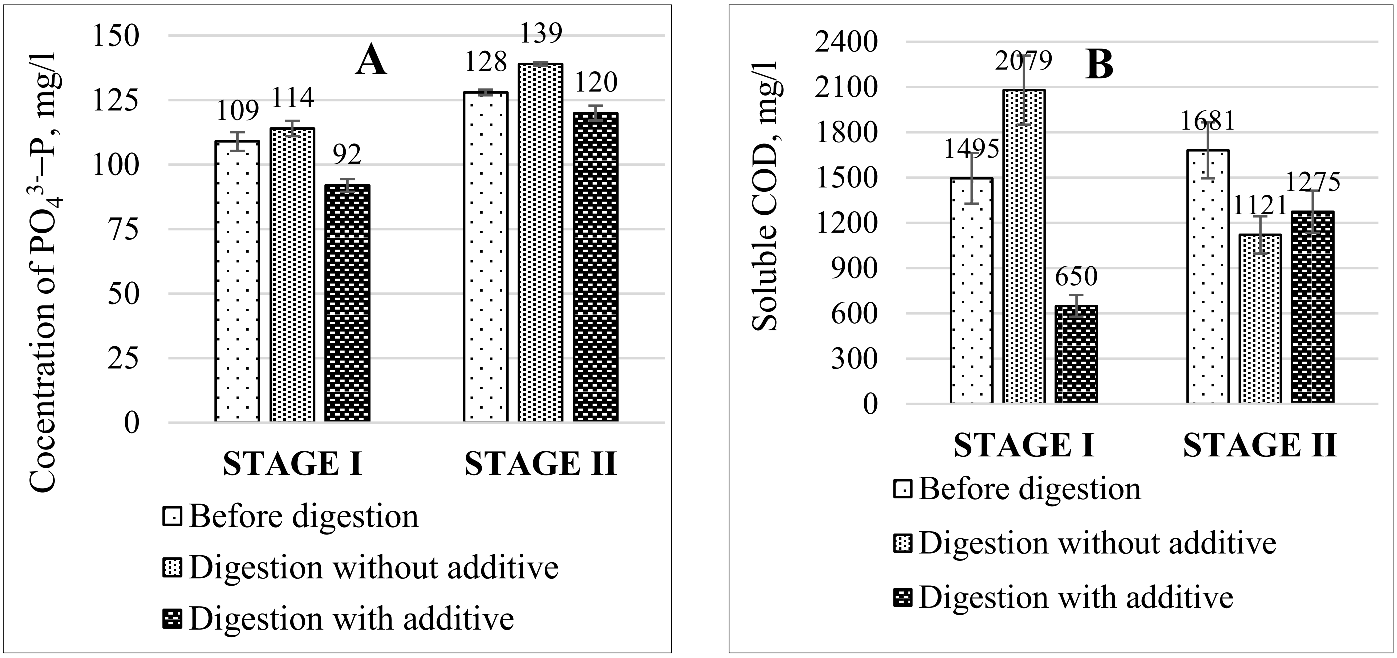

Figure 4. Concentration of phosphate phosphorus and soluble COD in supernatant.

Stage I (22.5 g/kg DM). It can be concluded that phosphate phosphorus was bound more efficiently at higher doses. During the anaerobic digestion process, phosphate is released from the sludge into the supernatant; however, according to G. Tchobanoglous et al. (Tchobanoglous and Eddy 2014), by addition of iron compounds to the digestion process binds soluble phosphate. As a result, the nutrient load of the WWTP and the risk of struvite formation can be reduced.

Figure 4 (B) shows that the soluble COD decreased by 25 % in Stage II but increased by 39 % in Stage I when the sludge was digested without the additive. This increase can be attributed to the relatively late onset of the sludge digestion process in Stage I; it began on day 8, reached its peak on day 17, and was still active on day 20 (Fig. 2). During the digestion process, microorganisms consume biodegradable organic matter, and the final product of the biological activity of methanogenic microorganisms is biogas. As a result, the value of soluble COD decreases during the digestion process.

The addition of iron with various morphologies and valence states during anaerobic digestion has attracted attention from researchers in recent years. It has been found that the addition of iron increases biogas production (hydrogen and methane) while simultaneously enhancing the breakdown of organic matter (Ma et al. 2015). This study has determined the optimal dose of the investigated additive for use in the anaerobic digestion process.

The results of this research were used to calculate the economic benefits for the Silute sludge treatment plants, which has an actual capacity of 870 kg DM/day. At this facility, a mixture of primary and excess activated sludge is digested under mesophilic conditions, followed by dewatering and drying. The following parameter values from the research were applied in the calculations: daily additive dose of 17.5 g/kg DM, an increase of VS degradation of 56.7 % due to the additive and increase in specific biogas production of additive of 11.5 %. Due to the additive. The rentability calculations, both without and with the additive, are presented in Table 5.

Table 5 compares two cases of sludge digestion: in the first case, the sludge is digested without an additive, while in the second case, the additive is applied. In the second case, a smaller amount of material remains after digesting, and 1.8 times more biogas is produced compared to the first case. Sludge dewatering requires 18% less polymer and saves nearly 9% of electricity in the second case. Additionally, sludge drying requires 8 % less heat and also saves 9% of electricity when the additive is used. Furthermore, the thermal energy production from biogas increases by 1.8 times in the second case. According to Table 5, the use of the additive in sludge treatment plants with a capacity of 870 kg DM/d can reduce the expenses for dewatering and drying of the digested sludge by up to 35 %. A shorter SRT when the additive is used allows for a reduction in the designed volume of digesters or an increase in the capacity of existing digesters. Overall, the use of the additive can significantly enhance economic profitability.

The additive accumulates in the sludge, which can be further treated by incineration and ash extraction. Sludge ash often contains significant amounts of phosphorus. In this study, the concentration of phosphate phosphorus in the supernatant decreased by 14–19 % due to the use of additive, indicating an increase in phosphorus content in the digested sludge. However, phosphorus concentrations in the sludge were not determined in this research. It is important to note that phosphorus is classified as a non-renewable raw material and is targeted for recovery from sludge ash through acid extraction (Ottigmosen et al. 2013; Fang et al. 2018).

Thus, the use of the additive can not only intensify the digestion process and improve biogas quality, but also help retain phosphorus for subsequent recovery from ash. Future research on the sustainability of materials is recommended.

Conclusions

The effect of a new iron oxides-based additive on the sewage sludge digestion process was investigated. The use of the

Table 5. Calculations of rentability without and with additive for the capacity of 870 kg DM/d.

Parameter	**Unit**	**Value**		
		Without additive	**With additive**	**Savings**
Technical parameters				
Amount of material after digestion	kg DM/d	726	660	
Biogas production	m^3/d	184	323	
VS amount in respect of DM	%	67.4	65.3	
Amount of evaporated water	kg H_2O/d	2823	2567	
Amount of additive	kg/d	0	15.2	
Prices				
Additive	EUR/kg	1.50		
Polymer	EUR/kg	4.00		
Electrical energy	EUR/kWh	0.08		
Thermal energy	EUR/kWh	0.10		
Dewatering				
Polymer dosage	g/kg DM	9	8	
Consumption of electrical energy	kWh/kg DM	0.20	0.20	
Polymer consumption	kg/d	6.5	5.3	
Consumption of electrical energy	kWh/d	145	132	
Drying				
Specific electrical energy consumption	kWh/kg_{H_2O}	0.11	0.11	
Specific thermal energy consumption	kWh/kg_{H_2O}	0.86	0.86	
Consumption of electrical energy	kWh/d	311	282	
Consumption of thermal energy	kWh/d	2428	2208	
Thermal energy production from biogas				
Production of thermal energy	kWh/m^3	4.90	4.90	
Production of thermal energy	kWh/d	901.6	1583	
Rentability				
Expenses for additive				
Additive	EUR/d	0.00	-22.80	-22.80
Expenses for dewatering				
Polymer	EUR/d	-26.00	-21.20	4.80
Electrical energy	EUR/d	-11.60	-10.56	1.04
Expenses for drying				
Electrical energy	EUR/d	-24.88	-22.56	2.32
Thermal energy	EUR/d	-242.80	-220.80	22.00
Profit from boiler				
Thermal energy	EUR/d	90.16	158.30	68.14
Total	**EUR/d**	**-215.12**	**-139.62**	**75.50**

additive reduced the SRT by 4–6 days and achieved maximum biogas production on average 1.6 times faster. The optimal dose of the additive was determined to be 0.35 g/g DM/20 days (17.5 g/kg DM). At this dose, VS degradation was 56.7 % higher compared to sludge digested without the additive. Moreover, biogas production increased by 75 %, and specific biogas production rose by 11.5 % due to the additive. The use of the additive also increased the methane concentration in the biogas by 8.4–18.2 %. Hydrogen sulfide reduction efficiency in the biogas was 55–62 %, and the concentration of phosphate phosphorus in the supernatant decreased by up to 19% when the sludge was digested with the additive. It was estimated that using the additive in a sludge treatment plant with a capacity of 870 kg DM/day could reduce the expenses for dewatering and drying of digested sludge by up to 35 %.

This detailed investigation of the increased efficiency of sludge digestion using the iron oxides-based additive provides new insights and may be valuable for future studies on the effects of iron oxides in anaerobic digestion process. The next stage could involve exploring the feasibility of regenerating the additives used in this study, as this is an important environmental issue related to the practical implementation of the anaerobic sludge digestion process.

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Ocena addytywnego wpływu na proces beztlenowej fermentacji osadów ściekowych

Streszczenie. Zastosowano dodatek na bazie tlenków żelaza, aby zmniejszyć ilość wytwarzanego osadu i zwiększyć zarówno produkcję, jak i jakość biogazu. Stosunek C/N przed fermentacją beztlenową wynosił 11,0–11,3, a pH kombinacji osadów wynosiło 7,3. Ustalona stosowana dawka dodatku wynosiła 0,35 g/g suchej masy osadu w okresie 20 dni. Pozwoliło to na skrócenie czasu retencji osadu do 6–11 dni, tj. mi. maksymalną produkcję biogazu osiągano średnio 1,6 razy szybciej. Test laboratoryjny przeprowadzono w VILNIUS TECH przy użyciu modelu fermentacji beztlenowej „W8 Armfield Ltd" (Wielka Brytania). Do badań wykorzystano dodatek na bazie tlenków żelaza. Dokonano pomiarów parametrów osadu i biogazu. Po dodaniu dodatku ilość lotnych substancji stałych ulegających rozkładowi wzrosła o 56,7%, ilość wyprodukowanego biogazu wzrosła o 75%, stężenie specyficznego wyprodukowanego biogazu wzrosło o 11,5%, a stężenie metanu w biogazie wzrosło o 8,4% do 18,2%. Po przefermentowaniu osadu z dodatkiem ilość fosforu fosforanowego w supernatancie zmniejszyła się aż o 19%, a skuteczność redukcji siarkowodoru w biogazie wynosiła od 55 do 62%. Koszt odwadniania i suszenia osadu przefermentowanego można obniżyć nawet o 35% w oczyszczalniach osadów, w których stosuje się dodatek na bazie tlenków żelaza.