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EFFECT OF FOOD WASTE CO-DIGESTION ON THE QUALITY OF THE DIGESTED SLUDGE AND LEACHATE PARAMETERS

Co-digestion of sewage sludge with other wastes allows a significant increase in energy production from fermentation gas, at the expense of a potential increase in the mass of sludge to be disposed of and the nitrogen load in the leachate. The paper presents the results of research on the co-digestion of sewage sludge with used frying oil and restaurant waste. The resulting increase in gas volume production was significant (60 and 45%, respectively) with virtually no increase in digester sludge mass. The capillary suction time tests showed no effect of co-digestion on the filtration properties of the digested sludge.

1. INTRODUCTION

Methane fermentation is one of the most advantageous solutions for sludge from the wastewater treatment process due to many economic benefits associated with the management of biogas for electricity and heat production [1]. Biogas production can be increased through a process of co-digestion with waste from the food sector. In addition to an appropriate increase in the benefits of gas use, co-digestion allows one to use the waste from other industries or municipal facilities [2]. This solution is increasingly appreciated and used worldwide, especially in Europe and the USA, where the co-digestion process is considered as one of the best ways to treat waste containing large amounts of easily biodegradable organic compounds [3–6]. However, the implementation of the full-scale co-digestion process has negative consequences associated with an increase in the mass of digested sludge and nitrogen load in the water from sludge dewatering.

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The increase in sludge mass results in higher costs of dewatering, drying, and transport. The potentially increased load of organic compounds or nitrogen in the digester liquor results in an increase of this compound in the mainstream or the deammonification process when it is used. After all, the load increasing results in the rise of aeration costs, which are often the largest operating cost of a WWTP. For example, removing 1 kg of nitrogen from wastewater costs about 1 PLN (0.2 €) in the case of the classic nitrification and denitrification process, and the cost of aeration for a large wastewater treatment plant (about 1 million pe) is in the order of several million PLN per year [7, 8]. Moreover, the growing legal requirements increase the costs of sludge management. Depending on the technological solution, these costs can reach 30–60 PLN/pe. The use of appropriately effective solutions allows for reducing these costs up to 30% [9]. The level of savings depends on local conditions, so each intention to implement co-digestion should be preceded by a detailed analysis of all important aspects of the process, in particular, the impact of possible implementation on the production of biogas, digested sludge production, its dewaterability, and leachate parameters. This requires appropriate experimental studies to estimate the technological effects resulting from the change in the operating conditions of anaerobic digestion reactors. This article aims to present selected results of such an analysis (in connection with the plans to implement full-scale co-fermentation in Wrocław WWTP), based on the results of technological experiments of co-digestion of two types of waste and sewage sludge. Experiments were carried out in a continuous stirred tank reactor (CSTR) on a laboratory scale working with technological parameters corresponding to the operating conditions of the anaerobic digestion in WWTP (AD-WWTP).

2. MATERIALS AND METHODS

Digestion reactors. The experiment was set up in 3 laboratory research reactors working with parameters reflecting the actual operating conditions of the AD-WWTP. The first of the digester reactors (DR1) served as a reference (only fermentation of sewage sludge), and the other two (DR2 and DR3) were used to study the effects of co-digestion of sewage sludge with the addition of waste from the catering sector in the amount of respectively 1 g/d of frying oil and 8 g/d of restaurant waste (D2 and D3), as an addition to 160 g/d of raw sludge (to all reactors). The reactors with a working volume of 5 dm³ were operated at a constant temperature of 37 °C, maintained by an ultrathermostat. The sludge age (equal to the hydraulic retention time) was 29–31 d. The reactors were equipped with mechanical stirrers and Ritter MGC-1 V3.4 PMMA fermentation gas flow meters with a nominal flow of 500 cm³/h and a minimum flow of 1 cm³/h. The amount of co-digested waste was determined based on preliminary estimates of the gas production potential so that the expected increase in production would be 20–50% of the base production resulting from the digestion of the sludge alone. Each

of the reactors was supplied with a mixture of sludge from WWTP: primary sludge from primary settling tanks and excess sludge from the biological reactor after mechanical thickening. The added primary sludge constituted about 59%, while the remaining 41% was excess sludge. The method of feeding, the loading rate, hydraulic retention time corresponded to the operating parameters of the actual AD-WWTP (Table 1).

Table 1

Working parameters of laboratory reactors and AD-WWTP

| Parameter | AD-WWTP | Digestion reactors |
|-------------------------------|--------------------------------|---------------------------------|
| Volume | 39 000 m ³ | 5 dm ³ |
| Primary sludge (thickened) | 741 m ³ /d | 65 g/d |
| Excess sludge (thickened) | 507 m ³ /d | 95 g/d |
| Raw sludge (primary + excess) | 1248 m ³ /d | 160 g/d 6.37 g VS/d |
| Frying oil | none | 1 g/d (DR2 only) 0.90 g VS/d |
| Restaurant waste | none | 8 g/d (DR3 only) 1.72 g VS/d |
| Hydraulic retention time | 31.2 d | 31.2 d |
| Loading rate | 1.17–1.25 kg VS/m ³ | 1.27 kg VS/m ^{3a} |
| VS reduction | 43–46% | 50.3% |

^aLoading rate without waste addition.

VS – volatile solids.

Sludge and soluble fraction analytics. During the experiment, the composition of the substrates (primary sludge, excess sludge, frying oil, restaurant waste) and digested sludge were analyzed in terms of total solids (TS), volatile solids (VS), mineral solids (MS), total nitrogen (TN), chemical oxygen demand (COD) and pH. Additionally, the soluble fraction was analyzed for ammonium nitrogen, alkalinity, volatile fatty acids (VFA), and COD. The sludge analysis was performed once a week throughout the entire experiment. Hach cuvette tests were mainly used for the analysis, based on the spectrophotometric method with the Hach Lange DR3900 spectrophotometer. The types of analytical tests performed are presented in Table 2. The characteristics of raw substrates (raw sludge, frying oil, and restaurant waste) are presented in Table 3.

The capillary suction time (CST). During the research, an analysis of the digested sludge dewatering was also carried out by measuring the capillary suction time (CST) for different doses of polyelectrolyte used in WWTP (0–25mg polyelectrolyte/g VS). Apart from the digested sludge from digested reactors (DR1, DR2, DR3), the sludge coming directly from the AD-WWTP was also tested. The research was carried out for several doses of polyelectrolyte (Zetag 9048FS) about currently used in the operational practice of WWTP (12.5 mg/g VS). The measurement was carried out following BS EN

14701-1: 2007 and the experience of other researchers [10–12], with the use of a cylinder for easily dewatering sludge.

Table 2

Analytical tests performed

| Indicator | Analyzed stream ^a | Method | Measuring range |
|--------------------|---|--|---|
| TS/VS | RS, Fo, Rw, DS | direct weighting method | arbitrary |
| Total N bonded | RS, Fo, Rw, DS | Koroleff digestion (peroxodisulfate), and photometric detection with 2.6-dimethylphenol (Hach LCK 338) | 20–100 g TN/m ³ |
| COD | RS, RS _{sol} , Fo, Fo _{sol} , Rw, RW _{sol} , DS, DS _{sol} | dichromate mineralization (Hach LCK 014) | 1000–10 000 g O ₂ /m ³ |
| pH | RS, DS | pH probe WTW SenTix | 2.00–14.00 |
| NH ₄ -N | RS _{sol} , Fo _{sol} , RW _{sol} , DS _{sol} | Indophenol Blue (Hach LCK 303) | 2–47 g NH ₄ -N/m ³ |
| Alkalinity | RS _{sol} , Fo _{sol} , RW _{sol} , DS _{sol} | titration by 0.1 M HCl | 1–1000 eq/m ³ |
| VFA | RS _{sol} , DS _{sol} | esterification (Hach LCK 365) | 50–2500 g CH ₃ COOH/m ³ |

^aRS – raw sludge (excessive + preliminary), Fo – frying oil, Rw – restaurant waste, DS – digested sludge, subscript sol – soluble.

Table 3

The results of the analysis of the composition of co-fermentation substrates

| Substrate | Total fraction | | | | | | Soluble fraction | |
|-----------|--|----------------------------|----------------------|--------|----------------------|--------|--|--|
| | COD [g O ₂ /m ³] | TS [kg/m ³] | VS | | MS | | COD [g O ₂ /m ³] | NH ₄ -N [g NH ₄ -N/m ³] |
| | | | [kg/m ³] | [% TS] | [kg/m ³] | [% TS] | | |
| Fo | 2 635 947 | 904.1 | 904.1 | 100 | 0 | 0 | 2 635 947 | 278.5 |
| Rw | 274 492 | 215.5 | 208.9 | 96.9 | 6.6 | 3.05 | 53 200 | 87.5 |
| RS | 66 400 | 50.8 | 39.8 | 78.40 | 10.8 | 21.60 | 2 027 | 63.2 |

3. RESULTS AND DISCUSSION

3.1. INCREASE IN GAS PRODUCTION

Based on the recorded gas production and laboratory analyses, differences in gas production resulting from the addition of individual waste were determined. The results of the measured gas production in the stable operation phase (the second phase of the experiment), as the average of the individual values of daily production, are shown in Fig. 1.

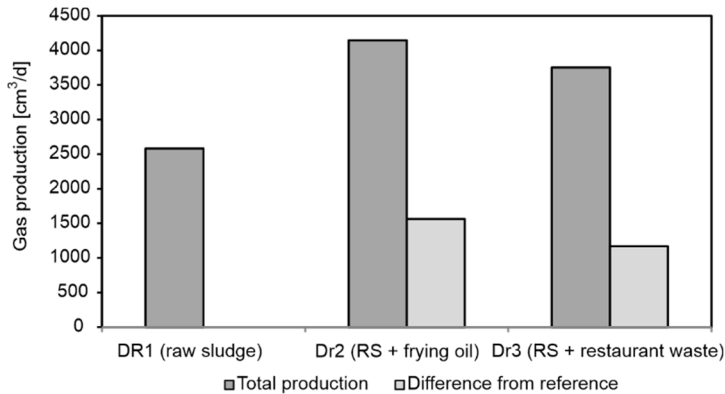


Fig. 1. Increase in gas production in the process of co-fermentation with waste

The unit gas production for oil was 1560 m³/t of frying oil (1560 cm³/g of added oil). However, the production for restaurant waste was 146 m³/t (1169 cm³ per 8 g of added waste). This means an increase in gas production by 60 and 45%, respectively, compared to the reference reactor. The further part of the work presents the effect of co-digestion on the digested sludge parameters and the composition of leachate, concerning their importance for the operation of the mechanical sludge dewatering and the effects of nitrogen removal from wastewater, in case of implementation in full scale in WWTP.

3.2. CHANGES IN THE COMPOSITION OF DIGESTED SLUDGE

Table 4 shows the results from the second phase of the experiment (the period of stable operation of the reactors) with the dosing of waste (to DR2 and DR3). Data from the initial and intermediate stages, when the doses of waste were gradually increased until the adopted base dose, were omitted.

Table 4

The results of the digested sludge analysis

| DR | | TS | VS | | MS | | COD | Total nitrogen | pH |
|---------------------------------------|---------|----------------------|----------------------|--------|----------------------|--------|-------------------------------------|-----------------------|-----|
| | | [kg/m ³] | [kg/m ³] | [% TS] | [kg/m ³] | [% TS] | [g O ₂ /m ³] | [g N/m ³] | – |
| DR1 (reference reactor) | minimum | 29.7 | 19.2 | 64.5 | 10.5 | 52.5 | 31 450 | 2 000 | 7.1 |
| | average | 30.4 | 19.8 | 65.1 | 10.6 | 53.5 | 35 750 | 2 172 | 7.3 |
| | maximum | 30.6 | 20.0 | 65.6 | 10.7 | 55.2 | 39 900 | 2 410 | 7.5 |
| DR2 (frying oil addition) | minimum | 29.9 | 19.4 | 64.8 | 10.3 | 51.0 | 30 850 | 2 080 | 7.1 |
| | average | 30.7 | 20.1 | 65.4 | 10.6 | 52.9 | 34 350 | 2 234 | 7.3 |
| | maximum | 31.7 | 20.6 | 66.2 | 11.1 | 54.4 | 37 380 | 2 310 | 7.5 |
| DR3 (restaurant waste addition) | minimum | 31.0 | 20.2 | 64.7 | 10.5 | 51.1 | 24 920 | 1 191 | 7.1 |
| | average | 31.4 | 20.5 | 65.5 | 10.8 | 52.8 | 30 560 | 2 093 | 7.4 |
| | maximum | 31.7 | 20.8 | 66.2 | 11.2 | 54.5 | 35 750 | 2 343 | 7.6 |

Figure 2 compares the daily dry solids loads (mineral and volatile) before and after digestion, respectively, for the digestion reactors DR1, DR2, and DR3 under their stable conditions. As can be seen, the co-digestion process was very effective in the aspect of removing a significant, additional organic load of waste, with the HRT as in the control reactor (and in the AD-WWTP). This indicates the possibility of significant loading increasing to AD-WWTP with the tested waste, without the need to increase their volume, with a marginal increase in the amount of digested sludge for disposal, and at the same time an excellent increasing of gas production (Fig. 1).

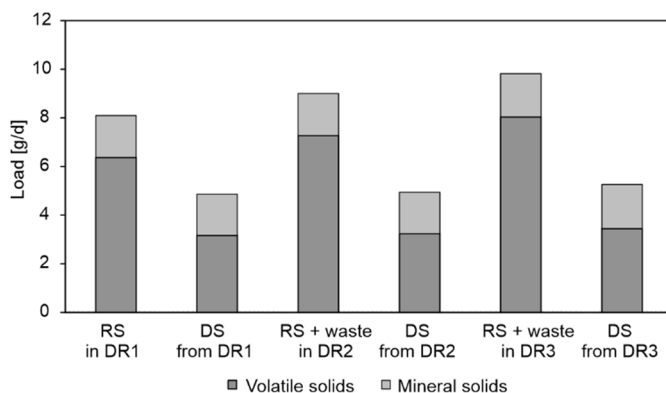


Fig. 2. Loads of the organic and mineral fraction of the raw sludge batch and digested sludge

Table 5 shows the increases in the amount of digested sludge (per unit mass of added waste) as a result of the co-digestion of the tested waste. These are the values resulting from the difference in the amount of digested sludge in DR2 and DR3 and the reference DR1.

Table 5

Indicator of the unitary increment in the amount of digested sludge as a result of co-fermentation of the tested waste

| Reactor | TS in wet matter of W [g TS/g] | Daily dose of TS of W [g TS/d] | Increase in the DS [g TS/d] | Increase of DS per total solids load of W [g TS _{DS} /g TS _w] |
|------------------------|--------------------------------|--------------------------------|-----------------------------|--|
| DR2 (frying oil) | 0.90 | 0.90 | 0.08 | 0.09 |
| DR3 (restaurant waste) | 0.22 | 1.72 | 0.41 | 0.24 |

TS – total solids, W – waste.

The waste used for co-digestion causes only a slight increase in the amount of dry solids of the digested sludge, especially in the case of frying oil. This slight increase is practically the entire organic fraction. As expected, the amount of the mineral fraction in this increment is negligible.

3.3. SOLUBLE FRACTION

Table 6 presents the results of research on the composition of the soluble fraction (leachate) in reactors during stable operation (second phase of the experiment).

Table 6

Characteristics of the soluble fraction of the digested sludge

| Reactor | COD | NH ₄ -N | Alkalinity | VFA | VFA/alkalinity |
|---------|-------------------------------------|--|----------------------|-------------------------|------------------------------|
| | [g O ₂ /m ³] | [g NH ₄ -N/m ³] | [eq/m ³] | [g VFA/m ³] | [g VFA/g CaCO ₃] |
| DR1 | 1723 | 914.0 | 71.6 | 340.3 | 0.095 |
| DR2 | 1736 | 829.2 | 66.8 | 338.3 | 0.101 |
| DR3 | 1861 | 1028.2 | 79.2 | 341.7 | 0.086 |

The results for the soluble fraction of digested sludge in DR3 show an approximately 10% increase (concerning DR1) in the concentration of organic compounds and ammonium nitrogen. The co-digestion of frying oil (DR2) did not increase the COD of the leachate and a few percent decrease in the concentration of ammonia nitrogen was noted. Alkalinity values and VFA and the VFA/alkalinity ratio, being an indicator of the quality and stability of fermentation reactors operation, indicates a remarkably similar stability reserve for all reactors.

3.4. DIGESTED SLUDGE DEWATERITY ANALYSIS

To estimate the potential influence of the tested waste on the effectiveness of mechanical dewatering of the digested sludge, a capillary suction time (CST) study was

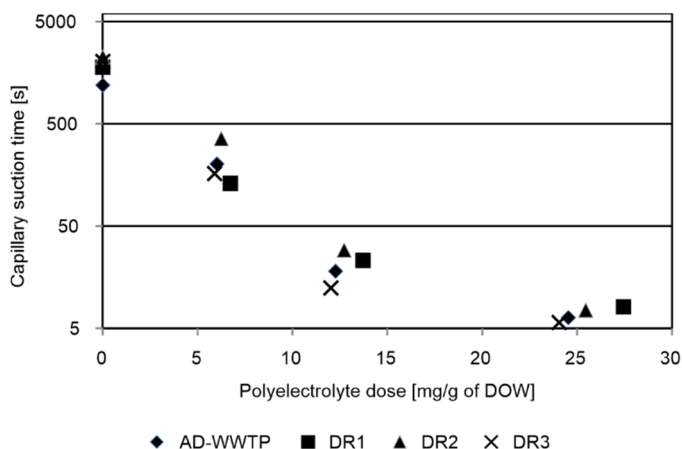


Fig. 3. Dependence of the CST value on the polyelectrolyte dose determined per gram of volatile solids of a given sludge

carried out. Each digested sludge from laboratory reactors (D1, D2, D3) and AD-WWTP was tested with four different doses ranging from 0-25 mg polyelectrolyte/gVS. The chosen doses of polyelectrolyte were close to the Zetag 9048FS dose currently used in the operational practice of WWTP. The test results are shown in Fig. 3.

The obtained CST values were similar (with a fixed dose of polyelectrolyte) for sludge from full-scale fermenters as well as no influence of co-digestion on CST was detected. Thus, it can be concluded the possible implementation of co-digestion of the studied wastes in the AD-WWTP will have not a negative effect on sludge dewatering.

3.5. CHANGES IN SLUDGE AND LEACHATE FLOW PARAMETERS AFTER IMPLEMENTATION OF COFERMENTATION IN WWTP IN WROCLAW

Changes in significant quantitative and qualitative parameters were estimated under the following assumptions:

- The water content of sludge after mechanical dewatering was assumed to be 80 wt. %. Currently, the WWTP filter presses achieve the final water content of 78–80 wt. %, and the CST tests confirmed a similar dewaterability of each sludge after co-digestion.
- Frying oil did not add water to the co-digestion process.
- Frying oil did not add any nitrogen load.
- The amount of water from kitchen waste in the inlet and outlet of the co-digestion process were similar.
- The change in sludge volume due to gas production and water evaporation was neglected.

Table 7 shows the values of the the amount of individual wastes in the reactor inlet and outlet.

Table 7

Waste mass in the reactor batch and volume waste in the digested sludge per reactor volume unit

| Waste | Batch for co-fermentation | | Digested sludge | |
|------------------|--|--|--|---|
| | Adopted waste density [g/cm ³] | Waste mass in the reactor batch [kg/m ³] | Waste residue in the sludge [dm ³ /m ³] | Digested sludge without residual waste [dm ³ /m ³] |
| Frying oil | 0.90 | 5.59 | 0.55 | 999.45 |
| Restaurant waste | 1.06 | 50.48 | 57.28 | 942.72 |

On basis of the difference between the volume of leachate after co-digestion with and without waste, the unit of leachate increasing was assumed (Table 8). Moreover, based on Table 6, additional COD and ammonium nitrogen loads from the supply of waste to the co-digestion process were estimated (Table 8). The increase in the mass of sludge was determined similarly, based on the values from Table 7.

Table 8

Change in selected quantitative and qualitative parameters per ton of waste

| Waste | Dewatered sludge mass increase [kg/t] | Dewatering effluent volume increase [dm ³ /t] | Increase in COD load in the leachate [kg/t] | Increase in NH ₄ -N load in the effluents [kg/t] |
|------------------|---------------------------------------|--|---|---|
| Frying oil | 56.6 | ca. 0 | 1.649 | ca. 0 |
| Restaurant waste | 54.3 | 863.2 | 2.696 | 3.792 |

The estimation shows that the addition of each ton of waste for co-digestion in AD-WWTP will result in an increase in the mass of the dewatered sludge by 54–57 kg. The addition of restaurant waste will result in a unitary increase in the leachate volume by 863 dm³, and in the co-digestion of frying oil waste, the leachate volume will not increase. Analyzing the possibility of an addition to AD-WWTP of several dozen tons per day of waste, additional production of digested sludge, leachate as well as COD and ammonium nitrogen loads (discharged with the leachate to the mainstream of WWTP) would be small fractions of the respective current values. If AD-WWTP would take ca. 80 t/d of restaurant waste, the expected increase in a load of ammonium nitrogen going to the mainstream will be about 250 kg NH₄-N/d. This gives an increase in nitrogen concentration in the inflow to the activated sludge reactors by about 2 g NH₄-N/m³. The analyzed WWTP is currently working at the limit of its ability to meet the nitrogen removal standards, thus it should be stated that the co-digestion of a significant amount of restaurant waste would require earlier creation of additional nitrogen removal capacity in the mainstream (e.g., by building leachate deammonification reactor). Co-digestion of frying oil will not decrease nitrogen removal effects.

4. SUMMARY AND CONCLUSIONS

As part of the experiment, 3 fermentation reactors were commissioned and operated, two of which were operated with an additional load of frying oil or restaurant waste. As expected, significantly higher production of fermentation gas was observed, which could be associated with economic benefits if this process is during implementation at the Wastewater Treatment Plant in Wrocław. The unitary gas production for waste was 1560 m³/t and 146 m³/t for frying oil and restaurant waste, respectively, which is an increase of 60% and 45%, respectively, compared to the reference reactor. There are many examples in the literature in which the addition of oil [13] or food residues [14] allows to increase the production of fermentation gas in the co-fermentation process.

The characteristics of the sludge and the soluble fraction in individual research reactors were analyzed. On its basis, the influence of co-fermentation on the possible increase in the mass of digested sludge for disposal as well as the quantity and quality of

leachate was estimated. It was found that, despite a significant increase in the load on the reactors, the efficiency of removing organic fraction from the sludge did not deteriorate. It turned out that the additional waste was almost completely fermented to methane. As a result, the increase in the weight of the digested sludge turned out to be relatively small, as it was 0.057 and 0.054 kg/kg for frying oil and restaurant waste, respectively. Very good fermentation effects came from the high biodegradability of the analyzed waste. In the case of this waste, it is possible to achieve biodegradability calculated as a loss of COD at the level of even over 93–99% [15, 16].

It was found that the co-fermentation of both examined wastes did not significantly worsen the susceptibility of the digested sludge to dewatering. It can be assumed that a properly selected dose of polyelectrolyte will allow us to obtain dewatering effects analogous to those currently obtained on the belt presses of the Wastewater Treatment Plant in Wrocław.

In the case of co-fermentation of frying oil, practically zero increase in the amount of leachate and the ammonium nitrogen load in this leachate was observed. The latter is particularly important in the case of treatment plants that do not have a reserve of nitrogen removal efficiency, as in the case of the facility on which the research was conducted. On the other hand, the increase in the COD load in the leachate per unit of mass of co-fermented waste was about 1.65 kg COD/t, which is practically insignificant for the operation of the main sewage treatment plant.

In the case of co-fermentation of restaurant waste, the unitary increase in the leachate stream is approximately 863 dm³/t. The additional loads of ammonium nitrogen and COD in this stream are approximately 3.79 kg NH₄-N/t and 2.7 kg COD/t, respectively. As in the case of frying oil, the increase in COD load is insignificant. The discharge of additional nitrogen load to the mainline of the treatment plant may be a significant obstacle in the way of implementing the co-fermentation of restaurant waste in a treatment plant with no reserve of nitrogen removal potential. This is the case of Wastewater Treatment Plant in Wrocław, currently operating at the limit of its efficiency in terms of the required nitrogen removal efficiency. Possible, upon implementation of restaurant waste co-fermentation at this treatment plant, an additional load of leachate would result in an increase in nitrogen concentration in sewage by about 2 g NH₄-N/m³. In such a situation, maintaining the currently required nitrogen removal efficiency in this treatment plant would require the elimination of the bottleneck of nitrogen removal capacity (e.g., by deammonification of leachate).

Summarizing, it can be concluded that the obtained results of the research allow us to recommend the implementation of frying oil co-fermentation in the anaerobic digestion of the Wastewater Treatment Plant in Wrocław. It can be expected to maintain the dewatering efficiency of the digested sludge in the existing belt press station and to meet the current requirements for the quality of treated sewage, including the nitrogen concentration.

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