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Management of liquid digestate in biogas plants

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Abstract

Due to rapid urbanization, increasing population, and developing living conditions, the amount of solid waste is increasing every year all over the world. Waste-to-energy technology, especially anaerobic digestion, is recognized as a potential and promising technology for sustainable and environmentally friendly energy production. This study aims to propose the management of the digester liquids produced in biogas/biomethane plants and classified as waste and to ensure that they are taken into consideration within the scope of the circular economy. With the help of existing literature, this research developed a systematic procedure that can be used to properly manage waste. This study proposed that a significant amount of energy recovery will be achieved with the establishment of facilities that produce biogas from domestic organic solid waste and other organic wastes.

Keywords: Advanced treatment; Anaerobic digestion; biomethane; digestate; renewable energy.

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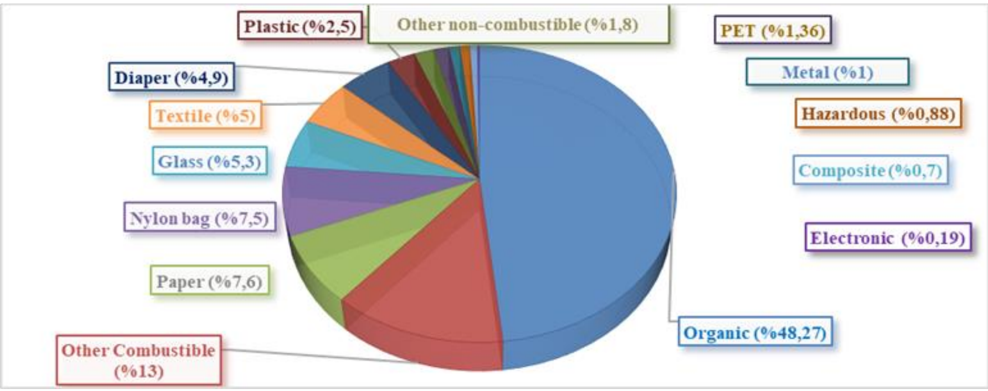
1. Introduction

Worldwide, 2 billion tons of municipal solid waste is produced every year, and this amount is expected to increase to 3.4 billion tons by 2050, according to future projections (Kaza et al., 2018). According to the 2018 data of the Turkish Statistical Institute, it has been reported that a total of 32.21 million tons of urban solid waste is produced annually in Turkey. The rate of waste produced in a day is calculated as 1.16 kg per person. Of the 32.21 million tons of waste collected by the district municipalities, 67.2 % (21.65 million tons) goes to landfills, 20.2% (6.50 million tons) goes to municipal garbage and 12.3% (3.96 million tons) are sent to recycling facilities. Istanbul was the province that produced the most waste in Turkey with 7.042,585 tons (22%) of waste in 2018 (TÜİK,2018).

1.1. Characteristics of municipal solid waste

Waste composition is the classification of material types found in domestic solid waste. Waste composition varies significantly with income level. As income levels increase, the percentage of organic matter in waste decreases. Goods consumed in high-income countries include more materials such as paper and plastic than in low-income countries. Because the organic composition of the wastes in our country is around 50%, Turkey exhibits an approach that is more suitable for the graph of middle-income countries. In 2014, a total of 31.12 million tons of solid waste was produced in Turkey and approximately 87% of it is urban solid waste, also known as municipal waste (Çevre & Bakanlığı, 2017). The waste characterization of Istanbul, which is the province that produces the most waste, is shown in detail in Figure 1.

Figure 1
Waste characterization of İstanbul



1.2. Management of municipal solid waste

Waste management practice is carried out within the framework of a procedure and is called the waste management hierarchy. Waste management hierarchy consists of prevention, reduction, reuse, recycling, energy recovery, and disposal headings in order of priority. Worldwide, almost 40% of waste goes to landfills, about 19% goes through material recovery, recycling, and composting, and 11% is processed through modern incineration. Globally, 33% of waste is still disposed of through exposure.

Waste disposal practices vary considerably by income level and region. Open dumping is common in low-income countries where landfills are not yet available. In low-income countries, around 93% of waste is incinerated or dumped on roads, open lands, and waterways. In high-income countries, only 2% of waste is released. As countries become economically richer, waste is managed using more sustainable methods. The construction and use of landfills is often the first step towards sustainable waste management. While only 3% of waste is landfilled in low-income countries, around 54% of waste is sent to landfills in middle-high-income countries. Economically rich countries tend to focus more on recovering materials through recycling and composting. In high-income countries, 29% of waste goes to recycling and 6% is composted. Incineration is also a common method, but in 2016 it was reported that 5% of global carbon emissions came from the incineration of solid waste. Therefore, the importance of sustainable solid waste management is underlined, and it is emphasized that wastes that are not collected/stored correctly will cause serious harm to the environment and human health (Kaza et al., 2018).

In the current situation in Turkey, there are many regulations and laws in the field of waste management. "Waste Management Regulation", which is one of the most frequently applied regulations, was published in 2015 and it is aimed to prevent and reduce waste generation, reuse of waste, waste disposal, and inspection activities with this regulation. The "Zero Waste Regulation", one of the most recently published regulations, was published in 2019 and it is aimed to effectively manage raw materials and natural resources, to establish and expand a zero-waste management system within the scope of this regulation.

Considering the current situation in Istanbul, 39 District Municipalities carry the wastes they collect from the borders of their responsibility areas to the Solid Waste Transfer Stations of IMM every day. Municipal waste generated in Istanbul in 2019 is approximately 18,100 tons per day. 6% of these wastes are disposed of by recycling, 11% by recovery, and the remaining 83% by landfilling (PDEU, 2020).

Due to rapid urbanization, increasing population, and developing living conditions, the amount of solid waste is increasing every year all over the world. It has been reported that 2 billion tons of municipal solid waste are produced every year around the world. It has been determined that only 16% of these wastes can be recycled, while 46% are disposed of as non-recyclable. The continuous increase in the amount of solid waste generated requires integrated solid waste management. The way for this integrated management to be sustainable is to use renewable energy sources. Waste-to-energy technology, especially anaerobic digestion, is recognized as a potential and promising technology for sustainable and environmentally friendly energy production (Beyene et al., 2018).

The produced biogas represents a useful source of green energy, while the by-product from the anaerobic digestion process is a waste that must be safely disposed of. This by-product from the anaerobic digestion process is called digestate (Đurđević et al., 2018). It is dense because it contains solid and liquid phases together. This digestate, which is described as liquid digestate, can be used both as a soil conditioner and as organic fertilizer with high free nitrogen and phosphorus value, which is easier to assimilate by plants. As a conditioner, it is valuable for its ability to improve soil structure, although its properties vary greatly depending on the biogas content.

1.3. Purpose of study

This study aims to propose the management of the digester liquids produced in biogas/biomethane plants and classified as waste and to ensure that they are taken into consideration within the scope of the circular economy.

2. Materials and Methods

2.1. Data collection

This research sought to propose systematic management of the digester liquids produced in biogas/biomethane plants. As such, data was collected based on previous literature, and the proposed method is described in detail.

2.2. Procedure

The research examined the existing waste management in detail and after a careful literature review, a new management system based on the acquired information was developed.

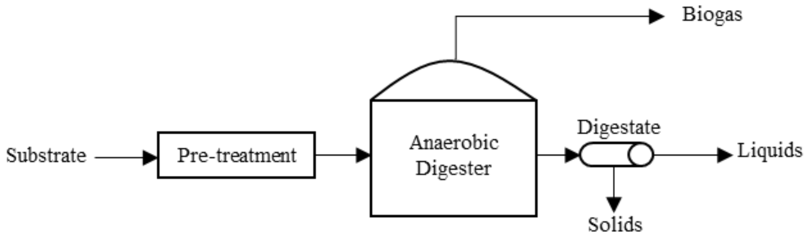
3. Results

3.1. Anaerobic digestion process

Anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. Anaerobic digestion (AD) is the result of a series of metabolic interactions between various groups of microorganisms. AD occurs in three stages hydrolysis, acid production (acidogenesis), and methane formation (methanogenesis). The first group of microorganisms secretes enzymes that hydrolyze polymeric materials into monomers such as glucose and amino acids. These are then converted to higher volatile fatty acids, H_2, and acetic acid, by the second group, i.e., acidogenic bacteria. Finally, the third group of bacteria, methanogenic bacteria, convert H_2, CO_2, and acetates to CH_4. AD is carried out in digesters maintained at temperatures between 30 °C and 65 °C (Verma, 2002).

Figure 2

Schematic diagram of anaerobic digestion



3.1.1. Hydrolysis stage

The breakdown of complex organic substances into simpler soluble volatile organic substances by fermentative and hydrolytic bacteria groups is called 'hydrolysis'. The most important factors affecting the hydrolysis rate are pH, temperature, and sludge age (Yıldız et al., 2009).

Hydrolytic activity is important in high organic wastes and can become rate-limiting. Some industrial processes overcome this limitation by using chemical reagents to enhance hydrolysis. It has been found that the application of chemicals to increase the initial step results in a shorter decay time and yields higher methane yields (Verma, 2002).

3.1.2. Acidogenesis stage

In the second part, acidogenic bacteria, also known as acid generators, convert the products of the first step, hydrolysis, into simple organic acids, carbon dioxide, and hydrogen. The main acids produced are acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). An acidogenesis reaction is shown in Equation 1:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

3.1.3. Methanogenesis stage

In the last stage of anaerobic treatment, the products formed in the other two stages are converted into methane gas by methane-forming bacteria. This transformation happens in two ways:

- Splitting of acetic acid molecules to produce carbon dioxide (CO_2) and methane (CH_4),
- Through the reduction of carbon dioxide (CO_2) with hydrogen.

Methanogenic bacteria include methanobacterium, methanobacillus, methanococcus, and methanosarcina. Methanogens are further divided into two groups acetate and H_2/CO_2 consumers. Methanosarcina spp. and methanothrix spp. They are considered important bacteria in AD, which are consumers of both acetate and H_2/CO_2. The methanogenesis reactions can be expressed as in Equations 2, 3, and 4:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2)$$

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (3)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (4)$$

The net heating value of methane gas under standard temperature and pressure is 35,800 kJ/m^3. Since anaerobic digester gas contains approximately 65% methane on average, the heating value of the digester gas is lower than this value (approximately 22,400 kJ/m^3). Its calorific value is low when compared to natural gas consisting of methane, propane, and butane. Biogas can be used as fuel for boilers and internal combustion engines (Yıldız et al., 2009).

3.2. Biomethane plant in İstanbul

On the European side of Istanbul (Kemerburgaz), a bio mechanization plant is planned to operate to obtain electrical energy from biogas by fermentation method in an oxygen-free (anaerobic) environment from organic solid wastes (such as food waste, vegetable-fruit waste, expired packaged food waste). In the first stage, the facility will be operated by feeding 90 tons/day of pre-treated organic waste to the biological process. It is planned to increase the non-hazardous waste recovery capacity to 350 tons/day via an additional line to be added to the scope of the project, without changing the area later on. The construction of the facility has been completed and also the trial tests have been completed. In Figure 3, the images of the plant are given.

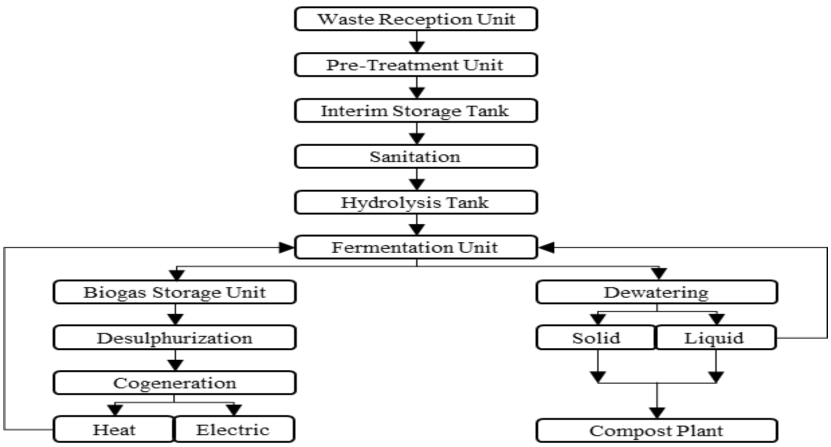
Figure 3

Biomethane plant in İstanbul

Only biodegradable wastes separated at the source will be processed in the Biomethanization Plant. Within the scope of the facility, the wastes brought to the facility by truck will be passed through the pre-processing unit where processes such as mechanical separation, sieving, and sand holding will be carried out and will be ready to be taken to the fermentation unit where biogas production will be provided. The biogas to be produced under anaerobic conditions in the fermentation unit will be stored in a double-layered membrane balloon and transmitted to the cogeneration units where heat and electricity production will be realized. Fermented waste taken from the fermentation units will pass through the dewatering unit, allowing for a separate evaluation of the solid and liquid phases. Some of the formed liquid phases will be fed back to the fermentation unit, and the remaining liquid phase and solid phase will be sent to the compost facility located south of the project site. The solid and liquid phases formed are very rich in content and suitable for use as fertilizer or soil improver. Figure 4 shows the flow chart of the plant.

Figure 4

Flow chart of the Biomethanization Plant



3.2.1. Waste reception unit

It is the place where the organic wastes collected as separately as possible at the source are kept before entering the process and fed to the facility. A waste reception unit is a place where the organic wastes coming to the facility can be accumulated for a maximum of 1 day. At the bottom, ground impermeability is provided to prevent the waste from contacting or leaking with groundwater, sewage, or surface water.

3.2.2. Pre-treatment unit

In the pre-treatment, the wastes are turned into a homogeneous and pumpable slurry for an effective anaerobic digestion process. For this, the organic waste coming to the facility is passed through stages such as crushing and liquefaction (mixing), wet screening, and sand holding in the pre-processing unit. The main functions of the preprocessing unit are:

- Separating impurities (plastic, glass, stones, metals, etc.) from waste to give the system a clean and pumpable organic slurry containing biodegradable organic matter,
- Removal of impurities such as sand and glass from organic waste to protect the biomethanization plant against excessive wear and tear.
- It is the treatment of wastes to ensure effective dissolution to increase the biogas flow rate in existing anaerobic digesters.

3.2.3. Hydrolysis tank

In the hydrolysis stage, the bacterial groups called fermentative and hydrolytic bacteria to break down the three basic elements of organic matter, carbohydrates $(C_6H_{10}O_5)_n$, proteins ($6C_2NH_33H_2O$), and oils ($C_{50}H_{90}O_6$) and convert CO_2, acetic acid, and most of them into soluble volatile organic substances. Since most of the volatile organic substances are volatile fatty acids, this step is also called the formation phase of volatile fatty acids [$CH_3(CH_2)_n$ COOH].

3.2.4. Anaerobic digesters

Biomethane production takes place in fermentation (digester) tanks. In this last stage of anaerobic fermentation, which starts in the hydrolysis tank and ends in the fermentation unit, methanogenic (methane-forming) bacteria groups come, and some methanogenic bacteria use CO_2 and H_2 to release methane (CH_4) and water (H_2O), while the other methanogenic bacteria group They form CH_4 and CO_2 using acetic acid. However, at this stage, the amount of methane formed by the first reaction is less than the amount of methane obtained by the second reaction. 30% of all produced methane is first; 70% is obtained by the second reaction. Methane bacteria, which come in the last stage of anaerobic fermentation and provide methane formation, are divided into three groups according to the temperature of the fermentation medium. These;

• Sacrophilic Bacteria: Optimum operating temperature is 25 °C,
• Mesophilic Bacteria: Optimum operating temperature is 36 °C,
• Thermophilic Bacteria: Optimum operating temperature 55 °C

Each main digester in the system operates under mesophilic conditions (37 to 42°C) and has a holding volume of approximately 19 days.

The material, which fills the waiting period in the main digesters, is transported to two final digester tanks, each with a volume of 2000 m^3, by pump and is kept in the final digesters for an average of 5 days. Biogas is collected through pipelines from the main digester and final digester tanks and delivered to the gas storage balloon.

3.2.5. Gas Storage Balloon

It is a unit consisting of 2 balloons covered with a membrane surface, where the produced biogas is stored. In cases where the energy conversion unit is not working, it allows the biogas produced to be stored within the planned period without being released into the atmosphere. Gas balloons made with double membranes have a total volume of 4040 m^3, 1040 $m^{3,}$ and 3000 m^3, and operate with a pressure of 25 bar.

3.3. Liquid Digestate Management Strategies

The rapid development of the biogas/biomethane industry in our country raises the problem of the management of digester fluids. Managing the liquid digestate produced by the anaerobic digestion of organic fraction of municipal solid waste (OFMSW) is the most important factor influencing the sustainable development of the biogas/biomethane industry. As an important solution to this liquid digestate problem, research is carried out to maximize the treatment methods and biogas/biomethane-dependent agro-ecosystem balance (Wang et al., 2010).

After nutrient recovery processes such as liquid digestate, ammonia stripping, membrane purification, the high amount of nitrogen and phosphorus are recovered and used directly as liquid fertilizer, and the remaining water is either used as recycled water or discharged. In addition to these methods, it is a method that is on the agenda to be used in liquid digestate microalgae culture cultivation to produce biofuels or bioproducts. Because using digester liquid to grow microalgae reduces the nutritional cost.

As a result, when these management strategies are evaluated, the development and marketing of high value-added products by recovering the high nutrient values in liquid digesate is the ultimate solution for the future. The liquid fraction of the digester from OFMSW and food waste cannot be used directly for agricultural purposes without further processing (Malamis et al., 2014). Many wastewaters treatment and nutrient recovery techniques, given in Table 1, have been developed to treat or use the liquid digestate.

Table 1
Treatment techniques of liquid digestate

Digestate Type	Treatment Technology	Advantages	Disadvantages
Liquid	Membrane Purification	• Direct discharge. • Nutrient recovery for condensed forms.	• Disposing of condensed materials. • Pollution.
	Vacuum Evaporation	• Less volume. • Rich product in the scope of nutrients.	• Pollute with solids.
	Struvite Precipitation	• In this way, struvite can be recovered. • prevent pollution in pipes.	• Pollute with solids. • Safety issues.
	Ammonium Stripping	• No barriers to using in the lands. • Ammonium sulfate as fertilizer.	• High temperature and pH.
	Algal Cultivation	• Produces algae that can be sold or converted into biodiesel.	• Large surface area. • Complex bioreactor control.
	Waterland	• Lower power and operation fee. • Sanitation.	• Requires large surface area. • Long-term process (10-15
	Bio-oxidation	• Wastewater as fertilizer • Less disposing fee	• High power consumption.

3.3.1. Nutrient recovery

The two pretreatment techniques, membrane purification and stripping surface heat exchanger, are pretreatment technologies used to purify liquid digestate to obtain nutrient-rich concentrated liquids, purified water, or condensate. After volume reduction, the concentrated digester liquor can be further processed or used directly as liquid fertilizer to recover nitrogen and phosphorus, while purified water or condensate is either discharged or used as recovered water (Vaneeckhaute et al.,2012; Guercini et al., 2014).

During thermal or vacuum evaporation, it is necessary to lower the pH of the digester liquid to prevent ammonia from being stripped and to lower the ammonia levels of the condensate. It has been reported that 97.5% of the total nitrogen (TN) remains in the concentrate when the agricultural digester liquor is processed in a vacuum evaporation process, while the condensate contains 2.5% total Kjeldahl nitrogen (TKN), which represents 94.4% of the total inlet mass (Chiumenti et al., 2013). Li et al. (2016) compared the technical feasibility of vacuum evaporation and ammonium stripping.

The results show that ammonia stripping with the addition of calcium hydroxide ($Ca(OH)_2$) can achieve a relatively low nutrient concentration (total ammonia nitrogen (TAN) = 137 mg/L), while vacuum evaporation can achieve a much higher nutrient concentration (TAN) = 2998 mg/L). It is important to note that both processes are highly dependent on the initial pH of the digester (Li et al., 2016). Ammonia nitrogen (NH_4^+–N), phosphate (PO_4^{3-}), and chemical oxygen demand (COD) of 89%, 60%, and 44%, respectively, when the digester liquor, cattle manure, and fish industry wastes from the anaerobic co-digestion of lignocellulosic materials are subjected to the struvite precipitation process known to be purified. Although 89% of the NH_4^+–N of the digester is removed as struvite, external PO_4^{3-} is required for struvite precipitation when the digester is devoid of PO_4^{3-} (Estevez et al., 2014).

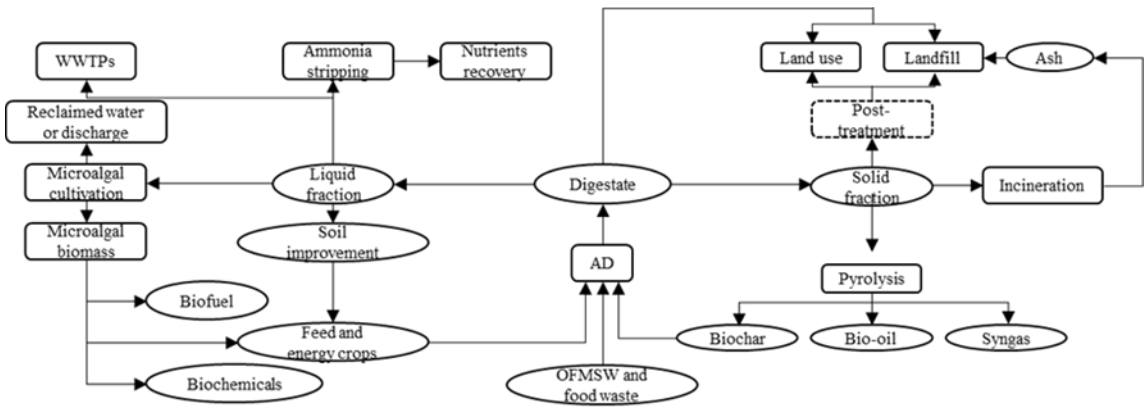
3.3.2. Biofuel or Bioproduct

Using digester liquid in microalgae culture to produce biofuels or bioproducts is a hot topic. Because using digester liquid to grow microalgae reduces the nutritional cost. Mixotrophic microalgae increase biomass productivity and improve the removal of nitrogen, phosphorus, and organic matter (Xia & Murphy, 2016). The high turbidity of the digester may lead to lower levels of photosynthetically active radiation that inhibits microalgae growth (Wang et al., 2010; Monlau et al., 2015). Ammonia inhibition may be another limitation for microalgae cultivation. To avoid ammonia inhibition, the digester needs to be diluted to 20–200 mg NH_4^+/L. Also, when the juice of the digester is used as a nutrient medium for algae cultivation, microorganisms from the digester may compete for nutrients (Croft et al., 2005).

In Figure 5, purification and evaluation methods are shown within the scope of OFMSW and digestate cyclical economy concepts resulting from the anaerobic digestion of food wastes.

Figure 5

Treatment technologies of digestate in the scope of circular economy



4. Conclusions

In the future, the best viable environmental option will be to generate energy from waste. Energy recovery technologies include waste incineration and anaerobic decomposition. In our country, the energy potential that can be recovered from organic wastes is quite high. Especially in a country like Turkey, where the potential for organic matter is very high, a significant amount of energy recovery will be achieved with the establishment of facilities that produce biogas from domestic organic solid waste and other organic wastes.

In our country, the production of biogas by using anaerobic digestion technologies in the organic part of urban solid waste, food, and similar industrial facilities, agricultural and animal wastes will both provide clean energy production and contribute to the reduction of environmental pollution. In addition, solid wastes stabilized as a result of the process can be used as fertilizer and soil conditioner. If sufficient incentives are provided by the government for the energy obtained from renewable energy sources, foreign and especially domestic treatment companies will take action to get a share from this large market. In this way, our country's energy deficit will be reduced, and employment will be created.

One of the most important problems of these biogas/biomethane plants is that they are difficult to operate. In addition, it is a problem how to evaluate the digestate that comes out of the anaerobic digester tanks and is considered as waste. Within the scope of this study, digestate purification and cyclical economy methods in solid, liquid, and mixed form were investigated. The advantages/disadvantages of the liquid digestate advanced purification and evaluation strategies, which are the subject of the study, were investigated in detail.

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