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Autor de correspondencia:

Juliana Berrío Uribe
Ingeniera Sanitaria e Ingeniera Ambiental
Universidad de Antioquia, Colombia
juliana.berriou@udea.edu.co

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Juliana Berrío[1]
Laura Catalina Ossa[1]

1. Universidad de Antioquia, Colombia

Abstract

The adoption of new forms of energy production is one of the challenges faced by countries worldwide due to the progressive depletion of fossil fuels. In this regard, the co-digestion of organic waste in Wastewater Treatment Plants (WWTP) has gained widespread acceptance, as it not only provides an alternative for the utilization of several types of biomasses to meet energy needs but also assists in waste management and nutrient recovery. However, accepting additional substrates for co-digestion requires careful physicochemical studies, as their characteristics can influence both the stability of the process and the quality and production of biogas.

In line with the above, this study implemented the case study method through descriptive analysis to evaluate the substrates accepted for anaerobic co-digestion in the Straubing WWTP in Germany (SER GmbH). As a result, it was found that floating fats (C1) and milk with inhibitors (C5) were the substrates that exhibited the highest biogas production per unit of treated mass, 90% more than distillation residues and 70% more than raw sludge.

These findings underscore the importance of carefully selecting substrates for co-digestion in WWTPs, highlighting the potential to harness valuable resources, as evaluated in this study, to increase efficiency in biogas production and, therefore, promote a more effective transition to sustainable energy sources in the global context.

The Straubing WWTP in Germany thus becomes an example of the possibilities offered by co-digestion in sustainable energy generation and waste management. The inclusion of floating fats and milk with inhibitors as successful substrates illustrates how research and careful implementation can optimize the performance of these facilities.

Keywords: biomass; fermentation; anaerobic co-digestion; biogas yield; substrates; wastewater treatment plant (wwtp); energy production; waste valorization; digester; organic load.

Análisis de sustratos aceptados para la co-digestión anaeróbica en la PTAR de Straubing, Alemania

Resumen

La adopción de nuevas formas de producción energética es uno de los retos que enfrentan los países a nivel mundial debido al progresivo agotamiento de los combustibles fósiles. En ese sentido, la digestión conjunta de residuos orgánicos en Plantas de Tratamiento de Agua Residual (PTAR) ha ganado gran aceptación, pues ofrece una alternativa para usar diferentes tipos de biomasa para satisfacer necesidades energéticas y ayuda en la gestión de residuos y recuperación de nutrientes. Sin embargo, aceptar sustratos adicionales para la co-digestión, supone estudios fisicoquímicos minuciosos, puesto que sus características pueden influir tanto en la estabilidad del proceso como en la calidad y producción del biogás.

En concordancia con lo anterior, el presente trabajo implementó el método de estudio de caso a través del análisis descriptivo para evaluar los sustratos aceptados para la co-digestión anaeróbica en la PTAR de Straubing en Alemania (SER GmbH). Como resultado, se encontró que las grasas flotantes (C1) y la leche con inhibidores (C5) fueron los sustratos que presentaron mayor producción de biogás por unidad de masa tratada, 90 % por encima de los residuos de destilación y 70 % sobre los lodos crudos.

Estos hallazgos subrayan la importancia de seleccionar cuidadosamente los sustratos para la co-digestión en las PTAR, destacando la posibilidad de aprovechar recursos potenciales, como los evaluados en este estudio, para aumentar la eficiencia en la producción de biogás y, por lo tanto, promover una transición más efectiva hacia fuentes de energía sostenible en el contexto global.

La PTAR de Straubing en Alemania se convierte así en un ejemplo de las posibilidades que ofrece la co-digestión en la generación de energía sostenible y la gestión de residuos. La inclusión de grasas flotantes y leche con inhibidores como sustratos exitosos ilustra cómo la investigación y la implementación cuidadosa pueden optimizar el rendimiento de estas instalaciones.

Palabras clave: biomasa; fermentación; co-digestión anaerobia; rendimiento de biogás; sustratos; planta de tratamiento de aguas residuales (ptar); producción energética; valorización de residuos; digestor; carga orgánica.

1. Introduction

One of the main challenges facing developed and emerging economies lies in the adoption of new forms of energy production due to the progressive depletion of fossil fuels, as well as concerns related to increasing greenhouse gas emissions (Benito et al., 2018; Barua & Kalamdhad, 2019; Almeida et al., 2022; Devarajan et al., 2022). In that sense, anaerobic digestion has gained great acceptance as it not only offers an attractive route for the utilization of distinct categories of biomass to meet energy needs but also helps in waste management and nutrient recovery (Nwokolo et al., 2020; Almeida et al., 2022). Considering that it is urgent to prove sustainable models for the treatment of waste that not only led to a reduction, but also take advantage of the energy potential (Emilio et al., 2022).

Anaerobic digestion, also called fermentation or biomethanation, is a biochemical process in the absence of oxygen, by which part of the organic matter contained in organic waste, is transformed thanks to the action of microorganisms, producing a mixture of gases (biogas) and digestate - fertilizer or fertilizer (Bareha et al., 2022; Nwokolo et al., 2020; Agustini et al., 2020; Zhang et al., 2018). However, in many biomethanation plants in the world, mainly those existing in WWTPs, anaerobic digesters could accept greater amounts of organic matter than they treat. This represents an opportunity to digest more biomass without added costs associated with the implementation of new infrastructure. And it is precisely from this approach that anaerobic co-digestion takes on great relevance, since from the same process the mixture of two or more substrates with complementary properties is used, so that, through their joint treatment, biogas production increases.

Similarly, Benito et al. (2018) and Tolessa et al. (2023), They pose the opportunity to overcome the drawbacks of mono-digestion through this technology, as the mixture of various materials improves the process and production of methane by increasing the availability of nutrients to microorganisms and the organic load, while reducing inhibitory chemical toxicity by diluting the co-substrates (Kunatsa & Xia, 2022; Agustini et al., 2018; Almeida et al., 2022). This eases the cost-effective operation biogas plants (Reyes et al., 2015).

Despite the many benefits of co-digestion, this technology requires careful monitoring and control, as there is no single set of usual working parameters that can be practical for all biodegradable organic waste. Considering this scenario, and that the availability of raw materials is wide in nature, further research should be carried out, focused not only on the characteristics of the substrate, but also on the optimization of biogas generation from them (Kunatsa & Xia, 2022). Because in fact, the composition of the substrate will influence the activity of the microbiological population, which in turn will greatly affect the long-term stability of the process, the degradation rate of solids and, consequently, the biogas yield (Reyes et al., 2015; Tolessa et al., 2023).

In principle, co-digestion plants should only accept and use pasty and liquid substances for co-digestion and which also meet quality criteria such as high organic content greater than 50%, good biodegradability (organic dry matter oTS > 50%), specific gas yield greater than 250 L CH4/kg organic dry matter oTS, pumpability less than 10 % TS, particle size less than 6 mm, free of impurities (tuft-forming fibers, stones, sand, plastics, etc.), permanent homogeneity, low nitrogen and phosphate content and low content of pollutants including heavy metals, organic contaminants, etc. (ATEMIS GmbH, 2014).

Despite many published studies on the co-digestion of different substrates, especially sewage sludge with various organic wastes, so far, few practical studies have been found on this process. This is mainly because the industry is generally not interested in publishing test data on a commercial scale (Arhoun, 2017). However, a review published in 2014 on the anaerobic co-digestion process shows that the main substrates used are: fertilizers of animal origin (54%), WWTP sludge (22%), organic portion of solid waste (11%) and others (13%). In this sense, the most used co-substrates are industrial waste (41%), agricultural waste (23%), municipal waste (20%) and others (16%); of which, industrial and municipal organic substrates have been shown to have the highest biogas production (Mata-Alvarez et al., 2014).

Biogas is a fuel produced from the decomposition or fermentation of organic materials (biomass) from organic waste

Revista EIA | https://doi.org/10.24050/reia.v21i42.1742

(vegetable and/or animal) in an anaerobic digester (Iweka et al., 2021). The suitability of biomass as a substrate for biogas production depends largely on its nutritional composition, which ultimately affects the biogas yield, methane content, biodegradability and decomposition kinetics of the respective biomass (Pessuto et al., 2016; Nwokolo et al., 2020). Earlier studies have established that the main nutritional components of interest to the substrate are carbohydrates, proteins and fats, as well as have shown theoretical estimates of the potential production of methane and the proportion of biogas that can be obtained from these nutrients as shown in the Table 1.

Table 1. Theoretical maximum biogas production and its percentage of composition

Nutritious	Methane yield (m3/Kg oTS)	CH4 (%)	CO2 (%)	Reference
Carbohydrates	0.42	50	50	(Nwokolo et al., 2020)
Proteins	0.50	50	50	(Nwokolo et al., 2020)
Lipids	1.01	70	30	(Nwokolo et al., 2020)

Similarly, different investigations have identified that factors such as digester temperature, retention time, raw material availability, co-substrate mixture ratio or nutrient balance, organic load rates (OLR), methane content of substrates and gas yield affect the biogas production potential during the digestion of the feedstock in the anaerobic process (Sillero & Solera, 2022; Brew-Hammond, 2010; Chow et al., 2020; Iweka et al., 2021). Therefore, it is essential to regulate all influencing factors properly for the process to work optimally.

1.1. The balance of nutrients C/N

This parameter represents the correlation between the amount of carbon and nitrogen present in organic matter. This ratio is the balance of food that a microorganism needs to grow to perform the digestion of organic matter (Chow et al., 2020). In this sense, from the literature, it is proposed that the optimal ratios of C / N in anaerobic digesters are between 20:1 and 30:1 to achieve an ideal ratio in co-digestion (Chow et al., 2020; Azarmanesh et al., 2023; Fernández-Rodríguez et al., 2019).

1.2. Digester temperature

Regarding temperature, mesophilic and thermophilic conditions are feasible depending on the substrates. Numerous researchers have highlighted the significant effects of temperature on the microbial community, process kinetics, and methane stability and performance (Chow et al., 2020). Lower temperatures during the process are known to slow microbial growth, substrate utilization rates, and biogas production, and can lead to cellular energy depletion, leakage of intracellular substances, or complete lysis (Chow et al., 2020; El Ibrahimi et al., 2021). Although higher temperatures generally increase biogas production, they also increase the release of more carbon dioxide from the liquid phase, which in turn decreases the calorific value of the gas combination (Fachagentur Nachwachsende Rohstoffe, 2010). Therefore, it is not the absolute temperature that is decisive for the stable control of the process, but the stability at a certain temperature level (Fachagentur Nachwachsende Rohstoffe, 2010). Hence, different temperature conditions are suggested to match different substrates, due to the characteristics of each of them. (Chow et al., 2020).

1.3. Organic Load Rates (OLR) and Hydraulic Retention Time (HRT)

Similarly, the OLR, parameter that accounts for the number of volatile solids (VS) or dry organic matter (oTS) that can be fed to the digester per m^3 of workload per unit of time (Fachagentur Nachwachsende Rohstoffe, 2010). On the other hand, the hydraulic retention time (HRT) is the time in which a substrate remains inside the digester until it is discharged, considering its composition and degradation. The optimal values for these variables depend on the type of substrate introduced into the digester, since the substrates determine the level of biodegradation activity that will occur in the digester (Chow et al., 2020; Groof et al., 2021).

Revista EIA | https://doi.org/10.24050/reia.v21i42.1742

1.4. Biogas yield

The yield represents the production efficiency of biogas, specifically methane from substrate degradation and which is mainly determined by the composition of the substrate, in other words, by the proportions of fat, proteins and carbohydrates (Nwokolo et al., 2020). However, this parameter alone is of little informative value since it does not include the effective load of the digester. For this reason, yields should always be considered in relation to the organic loading rate (Fachagentur Nachwachsende Rohstoffe, 2010). In general, biogas is a mixture of gases composed mainly of methane (CH4) and carbon dioxide (CO2), of which it is methane that becomes more relevant since it is the fuel component of biogas and, in this way, directly influences its calorific value (Fachagentur Nachwachsende Rohstoffe, 2010; Feng et al., 2023; Zhao et al., 2023).

It is in this way that it is proposed as a research objective to analyze, in terms of biogas performance, the substrates accepted for anaerobic co-digestion in the wastewater treatment plant (WWTP) of Straubing, Germany, to establish a basis for identification and prioritization of substrates, through theoretical-experimental correlations.

2. Methodology

In the present investigation, the Case study method through descriptive analysis to evaluate substrates accepted for anaerobic co-digestion at the WWTP in Straubing, Germany - SER GmbH (Martinez, 2006).

The review of the current state of the art on industrial waste used for anaerobic co-digestion in treatment plants, its characteristics, parameters, and incidences were carried out, using different scientific databases such as Scopus and Elsevier. Likewise, the theoretical data from which the company has been working historically and the data obtained in the fermentation tests carried out by the accredited laboratory were analyzed. The results are presented in a systematic way and interpreted objectively from the particular and through correlations.

2.1. Study site (company)

Straubinger Energie- und Reststoffverwertungs GmbH (SER GmbH), located in the city of Straubing (Germany), is the company in charge of accepting and treating the co-substrates or organic waste of high calorific value generated in the operation of different industries of the city, as well as generating and feeding energy into the local electricity grid as a result of the use (use and combustion) of the biogas produced in the fermentation process (Straubinger Entwässerung und Reinigung, n.d.)

2.2. Origin of substrates (sample)

The substrate sample was taken directly from the vehicle feeding the WWTP digester at its point of entry. In total, there were 6 samples corresponding to the substrates treated in the plant by 2022. These substrates were classified as shown in the Table 2. It should be clarified that for this case the company of origin of the waste is not specified for confidentiality and practicality in the presentation of the results.

2.3. Fermentation tests

In 2022, a certified laboratory was commissioned to carry out fermentation tests for the substrates shown in the Table 2. The samples had no pretreatment, and the test was performed according to the German standard DIN EN 12880 (2001), DIN 12879 (2001), DIN SN 51872-4 (1990), DIN SN 12176 (1998) and the VDI guide 4630 (2016) which provides uniform rules and specifications for the practice of fermentation tests and the determination of biogas yield. From these tests, dry matter (TS), organic dry matter (oTS), ignition residue (GR), biogas quality (% CH_4) and biogas yield and production were determined. The incubation temperature for this test was 37°C over a period of 34 days.

Table 2. Substrates evaluated in fermentation tests.

Substrate	Type
C1	Floating fats - Company A of the meat industry responsible for the slaughter and processing of poultry
C2	Plucking and washing water for chickens - Company A of the meat industry responsible for the slaughter and processing of poultry
C3	Excess sludge classified as floating fat - Company A in the meat industry responsible for the slaughter and processing of poultry
C5	Milk with inhibitors classified as flotation sludge - Dairy company
C6	Distillation residues – Ethanol industry
C8	Floating fats - Company B of the meat industry
Raw sludge	Primary clarifier sludge

3. Results and discussion

Specific gas yields and methane concentrations can be attributed to diverse groups of substances, on the understanding that in each case they result from different relative carbon concentrations. For the company SER GmbH, from the year 2012 and in the absence of current studies of each co-substrate, the biogas performance data provided in the database of the Bayerische Landesanstalt für Landwirtschaft – LfL were adopted, where the raw materials with the respective energy efficiency and some other reference values such as the methane content of the gas as a percentage by volume are listed. dry matter content, among others.

Table 3. Theoretical values established by the LfL for the different substrates.

Substrate	Type	TS [%]	oTS [%TS]	Nl/kg oTS	Nm3/t OS	CH4 [%]
C1	Floating fats	7	90	1000	43 o 63	68
C2	Water washed slaughterhouses	15	84	480	33 o 60.5	55
C3	Floating fats	7	90	1000	43 o 63	68
C5	Flotation sludge	-	-	705	81	65
C6	Distillation residues	8.5	96.5	621.3	51	58.9
C8	Floating fats	7	90	1000	43 o 63	68

TS [%] is the dry matter content in percentage, oTS [%] is the organic dry matter in % TS, Nl/kg oTS is the gas yield in standard liters per kg of organic dry matter, Nm3/t FM is the gas yield in standard cubic meters per ton of fresh matter and CH4 [%] is the Methane content of the gas as a percentage by volume. Data source: Biogasausbeuten verschiedener Substrate - Programm Berechnung - LfL (bayern.de).

In the Table 3 the values established by the LfL for the different substrates accepted by the company are observed and are calculated approximately, as far as possible, based on the average nutrient content (fats, proteins and carbohydrates) and digestive ratios. These calculated results represent the maximum possible gas yields and methane content under optimal fermentation conditions.

However, the tests carried out in 2022 found the real performance of some of the substrates accepted by the company (Table 4). These results allow us to specify which substrate provides the highest energy value for co-digestion, and to compare these findings with the theory used by the company over a considerable period. Banks et al. (2011) evaluated the benefits of co-digestion of food waste and manure, validating the co-substrate practice mentioned in this study and demonstrating improvements in the efficiency and sustainability of the process.

Table 4. Results of fermentation tests for different co-substrates accepted by SER GmbH.

Substrate	Type	TS [%]	oTS [%TS]	Nl/kg oTS	Nm3/t OS	CH4 [%]
C1	Floating fats	8.37	84	878	62	64.8
C2	Water washed slaughterhouses	7.11	89.30	532	34	63.40
C3	Floating fats	3.9	76.8	188	6	62
C5	Flotation sludge	12.4	93.9	733	86	64.5
C6	Distillation residues	0.87	64	722	4	57.8
C8	Floating fats	6.74		732	39	66.9
Raw sludge	PTAR residue	3.59	72.6	494	13	65.5

In the analysis of the quality criteria of the different substrates to which the fermentation test was carried out, which are important when selecting a co-substrate for joint digestion in a treatment plant, it was found that all substrates have a percentage of dry organic matter greater than 50% which implies highly biodegradable substrates that facilitate operation in short retention periods. Likewise, it is found that all have a pH within an optimal neutral range. It is expected that, in the joint treatment of the different substrates, at least during the methanogenesis stage, this variable will remain in a range of 6 to 7.8 units to facilitate the speed and amount of methane generated. However, in processes such as anaerobic fermentation, because in the stages of acidogenesis and acetogenesis some acids are formed, the pH values tend to work in slightly more acidic ranges. Additionally, studies such as the one conducted by Montoya et al. (2020) support that this factor cannot be generalized, as it is directly influenced by the type of substrate used. If variations occur, they may be due to the digestion of Volatile Fatty Acids (VFA) in the process, which increases the alkalinity of the medium. Therefore, it is of significant importance to know the acidity/basicity of the starting substrate, because depending on it you can know which residues to use together to control the system.

The fermentation tests were carried out under controlled laboratory conditions and at a fixed temperature of 37°C. This temperature, considered mesophile, favors the development and metabolism of methanogenic bacteria that are responsible for digesting organic matter. Other temperature ranges can be implemented in the process, but the results can be affected when measuring biogas production. However, Escarraga & Espinosa (2020) state that although conventional anaerobic digestion is carried out at mesophilic temperatures of 35-37°C, thermophilic anaerobic digestion has an advantage in terms of specific growth rate, faster metabolism, higher loading capacity, and consequently, higher methane yield.

To optimize biogas production, it is crucial to consider the digester configuration and operating conditions. Nizami and Murphy (2010) examine various digester configurations for biomethane production, which can contextualize the efficiency observed in the fatty substrates used in this study. This underscores the importance of appropriate infrastructure and technology to maximize biogas yield, as reflected in the results obtained in this study and in comparative studies.

Regarding the percentages of methane found in the biogas produced from the fermentation tests for the different substrates, they are acceptable according to the typical values reported in the literature, being desirable in all cases to obtain a percentage of methane higher than 60% (Figure 1). Previous studies have shown that substrates with a high lipid content, such as floating fats, tend to produce higher methane yields compared to those rich in proteins or carbohydrates. This is consistent with the results obtained for substrates C1, C5, and C8, which showed relatively high biogas yields, corroborating the literature reporting high methane yields for fatty substrates. Similarly, Krich et al. (2005) discuss the production of biomethane from dairy waste, providing comparative data on yield and gas quality, which supports the findings of high yields in fatty substrates.

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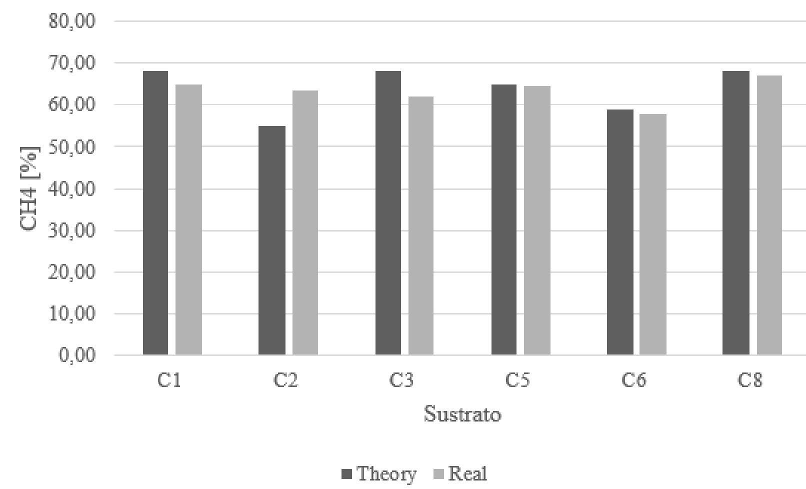
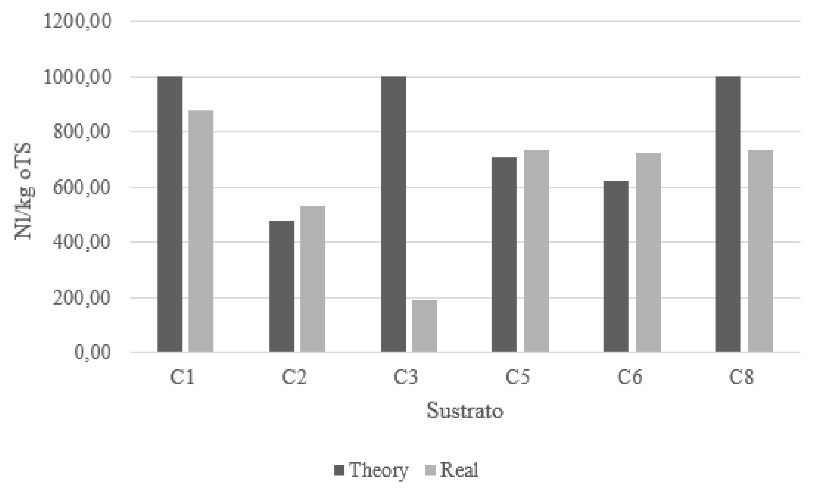
Figure 1. Quality of biogas analyzed in fermentation tests.



On the contrary, there were some considerable differences for biogas performance (Figure 2). The most appreciable dissimilarity is attributed to the substrate C3 corresponding to the excess of sludge from the meat industry, where the theory reports yield values of approximately 1000 Nl / Kg oTS while the tests yielded a value of 188 Nl / Kg oTS, value that also does not meet the minimum quality criteria of a substrate to be accepted for co-digestion, since in general terms the yield must be greater than 250 Nl/Kg oTS.

It should be noted that the fermentation test and therefore its results correspond to each substrate individually. In this sense, the importance of analyzing the quality criteria in an environment where the different substrates are mixed to determine more accurately the reasons for the significant differences found for the performance of each substrate is emphasized.

Figure 2. Biogas yield produced in fermentation tests.



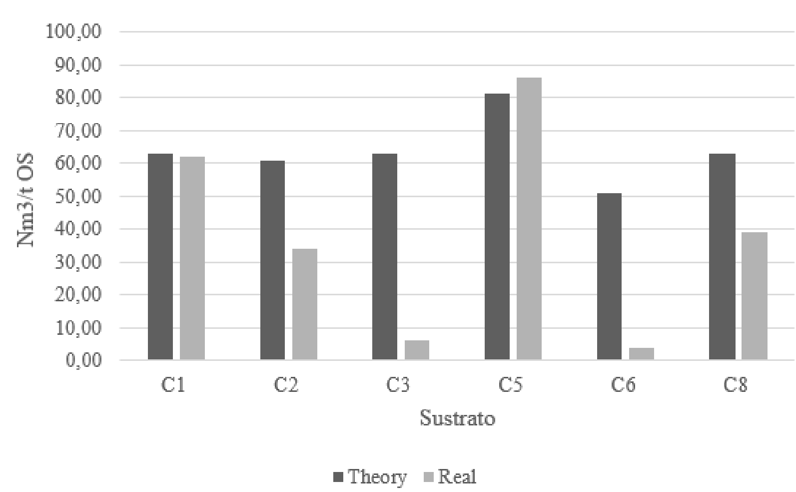
Similarly, large divergences were found in biogas production (Nm3/t OS) of substrates C3 and C6 when contrasted with theoretical values (Figure 3). This may be due to the low amount of dry organic matter present in these substrates, which limits the feeding of bacteria and thus the production of biogas. Additional studies, such as the one conducted by Angelidaki and Ahring (2000), highlight the importance of increasing the biogas potential from recalcitrant organic matter, which could explain the variations observed in the biogas yields for substrates C3 and C6.

However, it should be borne in mind that when working in a biological environment, only the average statistical indicators of long-term measurement series are reliable, provided that the conditions in which the tests are performed are considered.

On the other hand, in relation to the type of substrate, generally substrates with a higher proportion of carbon retained in resistant molecules such as cellulose, as is the case of the C6 substrate, will demand longer retention times. In that sense, the low biogas production of C6 may be linked to its nutritional composition. Chynoweth et al. (2001) analyze the production of renewable methane from biomass, providing additional context for the observed yields and suggesting that longer retention can improve the degradation of lignocellulosic materials.

Similarly, the frequency and intensity of agitation both in the reactors and in the fermentation, tests must be carefully selected so that there is a symbiotic balance between the bacteria present in the process. Otherwise, there will be a decrease in biological activity and therefore a reduction in biogas production. This can be associated with the divergence in the production of biogas from substrate C3 supported in turn with the laboratory test carried out at SER GmbH, where the fermentation test was carried out at 35 ° C for this type of substrate, where the main drawback was the mixture of the substrate and from which it was identified that, the longer the retention time, the higher the biogas production. This may be due to a substrate with a higher amount of carbon or low temperatures, since temperature is intricately linked to the times that the biomass must remain inside the digester to complete its degradation. In that sense, retention times decrease as the temperature increases.

Figure 3. Biogas production of substrates analyzed in fermentation tests.



In general, based on the gas yield in standard liters per kilogram of dry organic matter and the methane content, it is possible to affirm that the substrates that give a higher yield are C1, C5 and C8. This makes sense of the organic load present in these substrates, which are mostly lipids, which have a higher performance compared to proteins and carbohydrates. This result can be supported by Weiland

(2010), who provides an overview of the current state and prospects of biogas production, reinforcing the applicability of the substrates selected in this study.

The TS and oTS contents of these co-substrates vary greatly; This must be considered during acceptance and operation. The aim is to avoid temporary organic overload with highly concentrated substrates, as otherwise foaming in the digester could occur.

In this regard, different authors have detailed some key points to consider for improving co-digestion conditions. Thus, the review by Mao et al. (2015) on achievements in biogas research highlights the need for specific strategies for different types of substrates, supporting the need for process adaptations according to the type of raw material used. Additionally, Ward et al. (2008) provide strategies for optimizing anaerobic digestion, explaining variations in observed yields and suggesting possible improvements in operating conditions to maximize biogas production.

4. Conclusions

The use of industrial waste with high calorific value shows potential to increase biogas production and methane yield. It should be noted that the main challenges in anaerobic co-digestion technology are process instability, which is mainly due to inadequate substrate ratios, and operating conditions.

The composition of the biogas generated in the anaerobic digestion process of the different substrates is remarkably similar, with CH4 values ranging between 58 and 66%. Therefore, if the goal is to produce biogas with a high concentration of CH4, there is no reason to prefer a specific substrate.

The production corresponding to the substrate C3 from the excess of sludge of the meat industry, diverges approximately in 80% of the values reported in the literature for the production and yield of biogas. This result could be affected mainly by the nutritional composition of the substrate, the retention time, and the temperature of the test.

The results collected from the fermentation trials show a favorable performance for most substrates studied. However, it is highlighted that substrates C1 and C5, being residues with a rich and diverse characterization, provide more important nutrients for the process and that in co-digestion with the other residues have the potential to increase the production of biogas generated from their mixture.

Of the different substrates used for the fermentation tests, those corresponding to floating fats and milk with inhibitors showed higher biogas production per unit mass treated, 90 % more than distillation residues and 70% more than raw sludge approximately. This is because the composition of the samples is enriched with highly biodegradable available organic matter, which is clearly reflected in the amount of ST and SV obtained for each sample; However, the production achieved by other substrates analyzed is quite similar to the values reported in the literature, making them equally suitable for the joint treatment carried out in the company. In that sense, it can be concluded that of the co-substrates accepted by SER GmbH, milk with inhibitors and floated fats from the meat industry are the most feasible for integration into a WWTP, in terms of improving methane performance, operating and management costs.

Future research focused on the performance of biogas the different co-substrate in mixture is required to determine possible interruptions or inhibitions in the process. Similarly, study the optimization of operating parameters and the acceptance of new substrates from other industries.

It is also necessary to evaluate the environmental impact associated with this type of alternative. In accordance with the above, it is important to emphasize the interdisciplinary approach that these projects must acquire, considering that all environmental problems have an impact on people and that from the different branches alternatives can be planned that point to sustainable development and the circular economy (Chávez et al., 2022), bearing in mind that "the ultimate goal of any effort -be investigative, socioeconomic, cultural or otherwise, is the human being, and must tend to improve the living conditions of the entire population" (Farinango, 2017, p. 7).

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