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Bibliometric analysis on the applicability of anaerobic digestion in organic solid waste

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ABSTRACT

Anaerobic biological treatment can comprise a viable route of CH_4 production through the energy recovery of organic solid waste (OSW). This work therefore presented a bibliometric analysis of research trends on the theme "Applicability of biological treatment via Anaerobic Digestion in Organic Solid Waste", considering experimental articles published from 2018 to 2022 in the *Web of Science database™;* the analysis used VoSviewer software to define research trends, and found that the main terms addressed in the mapped scientific articles were anaerobic, waste, sludge, waste food, municipal waste, anaerobic co-digestion, sewage sludge, organic fraction, co-digestion and biogas. As a product of such mapping, an Interaction Network Diagram was constructed comprising the main terms in addition to a theoretical foundation on anaerobic digestion and biochemical and microbiological aspects about the process.

Keywords: anaerobic co-digestion, clean energy, food waste, microbial intercropping.

Análise bibliométrica acerca da aplicabilidade da digestão anaeróbia em resíduos sólidos orgânicos

RESUMO

O tratamento biológico por via anaeróbia pode compreender uma rota viável de produção de CH_4 através da recuperação energética dos resíduos sólidos orgânicos (RSO). Logo, neste trabalho apresentou-se uma análise bibliométrica das tendências de pesquisa acerca da temática "Aplicabilidade do tratamento biológico via Digestão Anaeróbia em Resíduos Sólidos Orgânicos", considerando artigos experimentais publicados no período do ano de 2018 ao ano de 2022 na base de dados da Web of Science™; para definir as tendências de pesquisa fez-se uso do software VoSviewer, que evidenciou que os termos principais abordados nos artigos científicos mapeados foram: *anaerobic digestion, waste, sludge, food waste, municipal solid waste, anaerobic co-digestion, sewage sludge, fraction organic, co-digestion* e *biogas*. Como produto de tal mapeamento construiu-se um Diagrama de Rede de Interações, compreendendo os termos principais, além de uma fundamentação teórica sobre digestão anaeróbia e os aspectos bioquímicos e microbiológicos sobre o processo.

Palavras-chave: co-digestão anaeróbia, consórcio microbiano, energia limpa, resíduos alimentares.

1. INTRODUCTION

The statistics presented by Word Bank point to an increase in the production of municipal solid waste of more than 2.2 billion tons per year by 2025, approximately 46% of the gravimetric composition of these are of organic origin.

In view of this, biological treatment via anaerobic digestion has been widely explored in order to enable methane production (CH_4) from the energy recovery of organic solid waste (OSW). Such treatment may help to address problems related to the intensive production of organic solid waste and the pressures on the exploitation of natural and nonrenewable energy resources (Tyagi *et al.*, 2018; Chen *et al.*, 2019; Cremonez *et al.*, 2021).

Biogas production (CH_4, CO_2 and others) comes from the conversion of volatile solids, and biogas production varies according to the operational conditions of digesters, in addition to the physical-chemical factors associated with the digestion process itself. Assam *et al.* (2011), Garcia-Peña *et al.* (2011), Di Maria and Baratta (2015) promote the applicability of biodegradable municipal solid waste to anaerobic digestion as a viable method of diversification in the renewable energy matrix, due to the energy potential of biogas, in addition to the biodigested and stabilized solid product, which is configured as an efficient organic fertilizer for agricultural use.

The scientific community reports that one of the disadvantages of using biodegradable OSW for anaerobic digestion is low nitrogen content, causing an imbalance in the C/N ratio. Therefore, the practice of anaerobic co-digestion of OSW as one of the substrates of the process began to be widely explored, associating it with several other residues that have high nutritional load. Aspects such as increased buffer capacity of the medium, balance in the C/N ratio, adequacy of moisture and total substrate solids and enrichment of the methanogenic microbiota may be some of the positive points for the applicability of co-digestion, in order to ensure the stabilization of anaerobic reactors, as well as to increase the yield of CH_4 (Angeriz-Campoy *et al.*, 2017; Chen *et al.*, 2019; Li *et al.*, 2022).

This study performed a bibliometric analysis on the applicability of biological treatment via anaerobic digestion in organic solid waste considering the articles that worked with experimental data published and indexed in the™ Web of Science database, restricted to the time series from 2018 to 2022.

2. METHODOLOGY

We searched the scientific literature for articles with experimental data published in indexed journals and available in the Web of Science database (WOS) during the period of 2018 to 2022. We focused on anaerobic digestion, seeking to highlight how the theme "Applicability of biological treatment via Anaerobic Digestion in Organic Solid Waste" has been framed in the scientific field, evidencing the trends of publications, the challenges in the research area and the countries that stand out in this field of activity.

For the analysis of the data in relation to the publications, we utilized the bibliometric tools available in the WOS database. To investigate the scientific trends in these publications, we used VoSviewer software, which establishes interactions and co-occurrences from the main terms present in titles and keywords extracted from articles published in the scientific literature.

3. RESULTS

3.1. Bibliometric analysis of data extracted from the Web of Science™ and scientific trends in research

For the search and selection of scientific articles, we investigated all entries on the themes "ANAEROBIC DIGESTION" and "ORGANIC SOLID WASTE",. using inclusion parameters of the time series from 2018 to 2022 and presented data from experimental research, and excluding review, conference or book chapters.

The searches returned 2102 technical-scientific articles for the research period (2018-2022). It was noticed that these articles were published in journals that fit the environmental sciences area, with 999 scientific papers; in Engineering, with 842 papers; and in Energy Fuels, with 579 papers.

The growing interest in research focused on Environmental Sciences, Engineering and Energy Fuels is understandable due to the pressing need to reduce environmental pressures exerted by anthropic activities linked to the energy sector and the growing production of solid waste. and then the field of engineering is strongly linked to the development of efficient and sustainable technologies, associated with the treatment of organic solid waste and the use of its by-products as a renewable contributor to the global energy matrix. It was observed that the ten countries that published the most about the theme between 2018 and 2022 were China, Italy, India, United States of America, Spain, England, Iran, Canada, Germany and Brazil (Table 1).

Table 1. Countries with the highest publication records.

COUNTRIES	PUBLICATION LOG COUNT	PERCENTAGE (%)
China	599	28.483%
Italy	223	10.604%
India	155	7.370%
United States	155	7.370%
Spain	144	6.847%
Brazil	99	4.708%
Australia	79	3.757%
Germany	79	3.757%
Canada	78	3.709%
Poland	73	3.471%

Source: Data extracted from WOS (2022).

Some of the countries mentioned in Table 1 are among the largest contributors to the high percentages of solid waste produced worldwide, shown in Figure 1, which presents the global generation of municipal solid waste by country for the year 2017. According to world bank data (2018) the United States, China, India and Brazil generated the largest quantities, and the USA has the largest per capita generation of 2.6 kg/day of waste produced, which may justify further scientific research in these countries on the theme in question.

To investigate the scientific trends in these publications, the VoSviewer software was used, which establishes interactions and co-occurrences from the "main terms" present in titles and keywords extracted from the articles published in the scientific literature of WOS. The software mapped the presence of 36,282 terms, which were used in titles and keywords in the scientific literature published in WOS during the years 2018 to 2022, of which the ten most recurrent were: anaerobic digestion, waste, sludge, food waste, municipal solid waste, anaerobic co-digestion, sewage sludge, fraction organic, co-digestion and biogas (Figure 2).

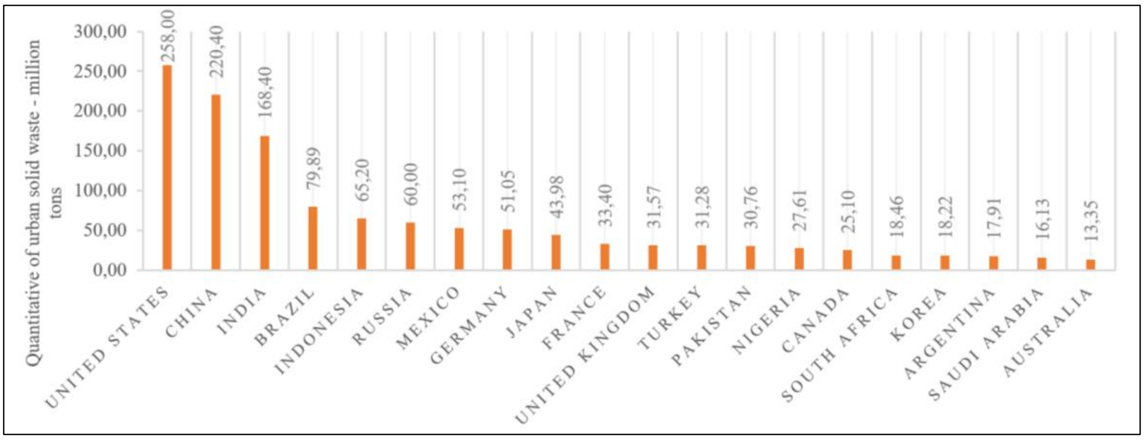

Figure 1. Global generation of municipal solid waste by country during 2017.
Source: Adapted from World Bank (2018).

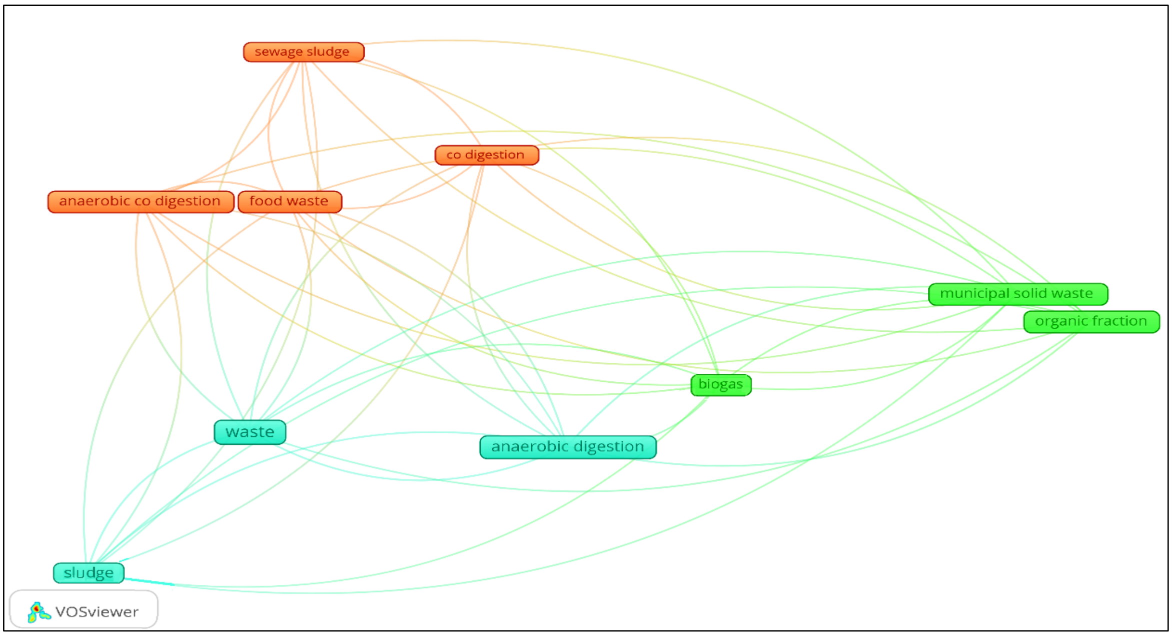

Figure 2. Interaction Network Diagram and Terms Co-occurrence.
Source: Prepared by the authors (2022).

Figure 2 shows the Interaction Network Diagram and co-occurrence of main terms created by the software from the scan of scientific papers, considering as selection criteria the most recurrent terms, having a number of occurrences ≥50, that is, the keyword or term to be considered significant should have at least 50 or more occurrences in published works of scientific literature in the databases.

In addition, Figure 2 also shows the association between the main terms through cluster formation. The red-colored cluster comprised interactions between the themes of anaerobic co-digestion, co-digestion, food waste and sewage sludge; already the blue-colored cluster has anaerobic digestion, waste, sludge; and, finally, the green-colored one comprises the municipal terms solid waste, organic fraction and biogas. From the construction of the diagram interactions between terms, it was possible to establish the clusters present; precisely, the trends of what has been addressed by the literature on the theme "Applicability of Biological Treatment via Anaerobic Digestion in Organic Solid Waste".

Figure 2 shows the occurrence of anaerobic co-digestion in studies developed by the scientific community today, such practice is strongly associated with the nutritional enrichment of the microbiota present in anaerobic systems, besides assisting in the correction of several operational physicochemical parameters that may affect or inhibit the growth of bacterial and methanogenic populations.

Some parameters, such as the relationship between carbon and nitrogen (C/N), are commonly corrected through co-digestion. The optimal values of the C/N ratio surround the ratios of 20:1 – 30:1; outside these conditions, there are implications for microbial growth due to lack of nutrients, or excessive environmental toxicity (Chen *et al.*, 2019).

The literature includes studies using sludge or sewage sludge as an enrichment of the substrate for anaerobic co-digestion, precisely to correct factors such as C/N ratio, pH, low nutritional load for microbiota responsible for the degradation of organic matter, among other factors.

It is perceived through Figure 2 that the applicability of sludge has been one of the research trends in the area of anaerobic digestion and co-digestion, which can be justified by the fact that the sludge presents recycling potential due to its high nutritional load, being an efficient source of carbon, nitrogen and phosphorus (Zhao *et al.*, 2022).

Another factor that may justify the increasing use of sludge in energy processes such as anaerobic digestion may be with an interest in allocating large volumes of sludge is generated daily by the primary and secondary treatment of wastewater treatment plants, since inadequate management of this waste can also cause irreversible environmental impacts (Kim *et al.*, 2011).

As for Organic Solid Waste (OSW), Figure 2 also shows a growing interest in the literature in studying anaerobic digestion in organic waste stemming from food waste or loss. It is noteworthy that 44% of the gravimetric composition of the waste produced came from food waste and green waste and 2% from wood waste (World Bank, 2018). Such aspects of generation and composition can be associated in order to justify the growing tendency of the literature to develop experimental research involving the applicability of anaerobic digestion from the use of these percentages of OSW, especially when addressing the need for better management of these.

3.2. Rationale on anaerobic digestion in organic solid waste

In an anaerobic route, either in mono or co-digestion (Figure 3), the OSW, whether or not it comes from food residue, constitutes organic polymers, which can be biologically degraded to CH_4 and CO_2, involving at least two large groups of microorganisms. During hydrolysis (1st STEP) organic polymers, mainly insoluble, have carbohydrates and proteins in their composition, lipids, different fiber fractions, such as lignin, are decomposed into soluble monomers, such as monosaccharides, amino acids and fatty acids (Liu and Whitman, 2008; Shah *et al.*, 2014).

This metabolic process is performed by the first large group of microorganisms - hydrolytics - that excrete extracellular enzymes, such as hydrolases (amylases, proteases and lipases) that "couple" insoluble polymers, breaking them, resulting in products that will be used as carbon sources and electron donors in subsequent stages (Liu and Whitman, 2008; Shah *et al.*, 2014).

Shah *et al.* (2014) highlight that acidogenesis can occur bidirectionally, driven by hydrogenation and dehydrogenation processes, that is, referring to the inclusion of molecular hydrogen to monomers from hydrolysis; and conversely, the dehydrogenation that corresponds to the rupture of the hydrogen atom of the substrate.

The microbiota that conducts the acid phase (2nd STEP) are acidifying bacteria; these absorb low molecular weight products, using them as an energy source, and excreting aldehydes, carbon dioxide, hydrogen, short-chain organic acids (formime, acetic, propionic, butyric and pentatonic) and alcohols (methanol, ethanol) (Shah *et al.*, 2014).

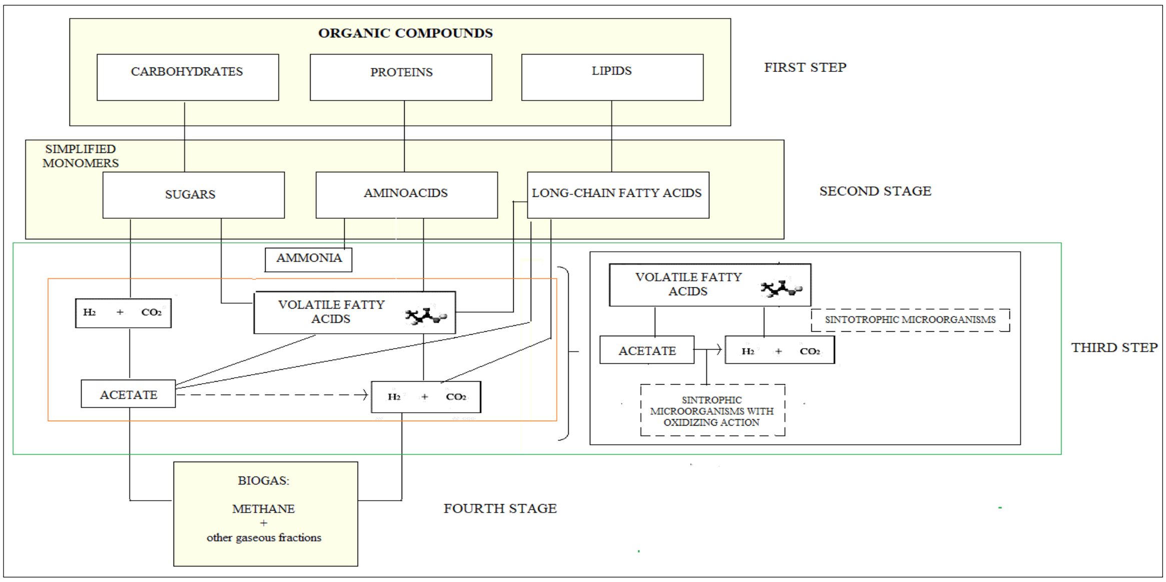

Figure 3. Diagram of metabolic routes of digestion of organic solid waste by anaerobic route. Legend: 1st Stage: Hydrolysis; Step 2: Acidogenesis; Step 3: Acetogenesis; Step 4: Menogenesis.
Source: Lettinga *et al.* (1996); Shah *et al.* (2014).

The fermentative stages of hydrolysis and acidogenesis comprise microbiological intercropping, which is mostly performed by the phylogenetic presence of the Bacteria domain, with Bacteroidetes and Firmicutes being the most recurrent phylum. However, there is still little clarity in sequencing the 16S rDNA gene for the hydrolytic and acidogenic microbiota, as well as for communities involved in adverse conditions, such as at high temperatures (Cardinali-Rezende *et al.*, 2016; Li *et al.*, 2022; Amin *et al.*, 2021).

Acetogenesis (3rd STAGE) is essential for the efficiency of methanogenesis, being the last phase of anaerobic digestion of organic compounds for biogas production, primarily CH_4 - comprises up to 70% of its composition - which arises from the reduction of acetates. During the acetogenesis phase, approximately 25% of acetates are formed and approximately 11% of hydrogen is produced in the digestion of process residues. Other products of the metabolization of matter are fatty acids and alcohols, which are not directly catabolized by methanogenic, requiring the synthesis action performed by autotrophic methanogenic strains and homoacetogenic bacteria, resulting in a secondary fermentation of organic acids in CO_2, H_2 and acetate (Shah *et al.*, 2014; Li *et al.*, 2022; Amin *et al.*, 2021).

For acetogenesis there is the action of specialized bacteria in converting products from the acid phase to acetate. However, among these products, volatile fatty acids are not easily metabolized, requiring the joint initiative of acetogenic bacteria in syntrophy with methanogenic archaeas. The literature reports the presence of the genera Syntrophomonas and Syntrophobacter during the conversion of these products (Shah *et al.*,2014; Rabii *et al.*, 2019).

The presence of hydrogen in the medium favors the clarity for methanogenic archaea, and although metabolic diversity is intense, some acetogenic microorganisms are unable to perform any reaction in pure culture, being necessary the symbiotic action of homoacetogenic bacteria with autotrophic methane bacteria, using the synotrophic action. In this context, it is understood that syntrophism is a process in which the digestion of an unwanted compound occurs from the interaction of two or more microorganisms and none of them can use this compound separately. As a result of this interaction within an anaerobic reactor, the production of triphosphate adenosine (ATP) from phosphorylation or oxidation of the substrate used in the metabolization of fatty acids and alcohols produced by other acidogenic microorganisms is produced. Finally, these compounds are converted into acetate that are used by methanogenics (Shah *et al.*, 2014).

During methanogenesis (4th STEP), the acetate produced in the previous stage is directly metabolized by acetoclastic and hydrogenotrophic methanogenic arches. The direct conversion of acetate to CH_4 is the responsibility of acetoclastics, while hydrogenotrophics convert hydrogen and carbon dioxide, derived from the syntrophic action of organic acids, for the production of CH_4 (Shah *et al.*, 2014; Li *et al.*, 2022).

The microorganisms responsible for CH_4 production are methanogenic, belonging to the domain of the Archaeas, are obligatory anaerobic and conduct methanogenesis from three routes: hydrogenotrophic, acetotrophic or acetochlortic and methyltrophic. The conduction before the respective routes is defined from the substrates commonly used, CH_3COOH, H_2 and CO_2, but other compounds can be produced (Table 2) (Hu *et al.*, 2018; Wang *et al.*, 2020).

Table 2. Common reactions during methanogenesis.

COMPOUND		PRODUCT
Hydrogen	→	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$
Acetate	→	$CH_3COOH \rightarrow CH_4 + CO_2$
Format	→	$4HCOOH \rightarrow CH_4 + CO_2 + 2\ H_2O$
Methanol	→	$4\ CH_3OH \rightarrow 3CH_4 + CO_2 + 2\ H_2O$
Carbon monoxide	→	$4CO + 2\ H_2O \rightarrow CH_4 + 3H_2CO_3$
Trimethylamine	→	$4(CH_3)3N + 6\ H_2O \rightarrow 9CH_4 + 3\ CO_2 + 4NH_3$
Dimetilamina	→	$2(CH_3)2NH + 2\ H_2O \rightarrow 3\ CH_4 + CO_2 + 2NH_3$
Metilamina	→	$4(CH_3)NH_2 + 2\ H_2O \rightarrow 3\ CH_4 + CO_2 + 4NH_3$
Methyl mercaptans	→	$2(CH_3)_2S + 3\ H_2O \rightarrow 3\ CH_4 + CO_2 + H_2S$
Metais	→	$4Me0 + 8H^+ + CO_2 \rightarrow 4Me^{++} + CH_4 + 2\ H_2O$

Source: Taken from Shah *et al.* (2014).

The microbiota acting on methanogenesis are extremely sensitive to temperature and pH variations, besides having its growth inhibited by high rates of volatile fatty acids, hydrogen, ammonia and sulfur in the medium (Shah *et al.*, 2014; Wang *et al.*, 2018; Amin *et al.*, 2021).

3.3. Influence of hydrogen ionic potential (pH) during anaerobic digestion

The pH is the factor that directly influences the microbiological activity during the metabolization of organic matter and suffers the action of virtually all monitoring parameters, such as: the substrate itself has a range in which the pH fits; the composition of the substrate and the first stage of its metabolization can result in volatile acids, which favor pH decay; the presence of free ammonia (NH^{3+}) or ammonium ion (NH^{4+}) reflects in the decay of the pH; these and other factors may lead to variations in the pH range present in the ecosystem in which digestion occurs (Meegoda *et al.*, 2018; Li *et al.*, 2022).

The literature commonly reports anaerobic digestion performed in reactors as two major stages: hydrolysis/acidification and methanogenesis, which induces to characterize the first stage of the process as acidic and the second as neutral. However, studies already return varied ranges for the different types of microorganisms that act on the consumption of organic matter, and these ranges should be suitable even for the growth of the microbiota and subsequent performance (Srisowmeya *et al.*, 2020; Cremonez *et al.*, 2021).

The group of hydrolytic bacteria initiate their growth often in slightly acidic to alkaline media. PH values < 4.0 can suppress the growth and performance of hydrolytic enzymes. With the appearance of soluble compounds, there is the beginning of microbiological activity of acidogenics – ideal range of action between 5 and 6.5 contemplating the formation of short-chain organic acids (acetate, propionate and butyrate). These acids can accumulate in the medium and favor excessive pH decay and lead to medium instability (Cremonez *et al.*, 2021; Li *et al.*, 2022).

As fatty acids and alcohols are not directly catabolized by methanogenic archaea, acetogenic bacteria have the action to metabolize acidogenesis products, transforming them into substrates for subsequent stages. While the acetogenic microbiota is established in the medium, there is an increase in the pH of the same, being a critical factor in relation to acidogenic bacteria, leading to the disruption of the cytoplasmic membrane; that is, there is a substitution of the microbiota in the medium, dictated by the variation of pH, and it is found that the reaction medium is in ideal conditions for methanogenic activity at rates between 6.5 - 8.2 (Bajpai, 2017; Amin *et al.*, 2021).

3.3.1. The presence of volatile fatty acids (GVA) in the reaction medium

Volatile fatty acids (GVA) are products of the acid phase of the anaerobic reactor and directly influence the presence of methanogenic strains. The acids commonly reported in the literature present in acetic anaerobic digestion, propionic acid, butyric acid, valvalesse acid, succinate acid, and others, and behave with metabolic constituents during acetogenesis, serving as a substrate for the synthetic action of homoacetogenic bacteria and autotrophic methane bacteria. The persistence of AGVs in the reaction medium causes the inhibition of several methanogenic groups, due to the decay of the pH. The methanogenic microbiota has optimal acclimatization conditions ranging from 6.5 to 8.2 (Shah *et al.*, 2014; Li *et al.*, 2022).

3.3.2. Influence of temperature

Microorganisms have a specific classification according to the ideal range of acclimatization and performance in the digestion of organic matter; the literature reports higher activities in mesophilic conditions, with an optimal temperature around 35°C, due to the better control of the operational conditions of the reactor. However, studies indicate an interesting behavior regarding the reduction of recalcitrant matter in the system when the operation takes place at thermophilic temperatures, having its ideal range for action around 55°C. High temperatures result in an increase in reaction speed, which implies an increase in the speed in the conversion of organic load, in a shorter holding time. In addition, there is a medium that causes the lysis of possible pathogens present in the medium (Kasinath *et al.*, 2021).

Significantly, the literature usually performs the operation of anaerobic reactors under mesophilic conditions, due to ease of operation, lower energy cost, besides favoring ideal ranges for CH_4 production, between 30 - 40°C (Khalid *et al.*, 2011; Wellinger *et al.*, 2013).

3.3.3. Influence of Carbon and Nitrogen (C/N) relationship of reaction medium

The relationship between carbon and nitrogen represents the nutritional balance that anaerobic microorganisms need to grow. Optimal values of the C/N ratio surround the ratio of 20:1 – 30:1; outside these conditions, there are implications for microbial growth, due to lack of nutrients, or toxicity of excessive proportions in the environment (Chen *et al.*, 2019).

The excessive presence of carbon can lead to acidification of the medium, due to the presence of GVA. And, nitrogen, which is an inorganic nutrient essential for the biological growth of microorganisms acting mainly in protein synthesis, in anaerobic reactors, when at unwanted concentrations of 1800 g/L, in the forms of ammonia and organic nitrogen, the inhibition of microbial consortia for the production of CH_4 (Chen *et al.*, 2019; Chatterjee and Mazumder, 2020).

The literature commonly uses this parameter to justify the applicability of anaerobic co-digestion, since in substrates that have a low relationship between carbon and nitrogen it is indicative of low digestion efficiency. Therefore, co-digestion is based on mono digestion practices (Chatterjee and Mazumder, 2020).

3.3.4. Influence of applied organic load

Another fundamental parameter is the applied organic load (OLR), being expressed by the quantity of organic matter in terms of chemical demand, mass of oxygen or volatile solids, per unit of time applied in the reactor, in a volume unit. There is greater stability in relation to the microbiota present in the reactor when it has ideal amounts of OLR, serving as a substrate for microorganisms to develop. However, overload or shock can result in rapid degradation of macromolecules, leading to the accumulation of volatile fatty acids, leading to the acidity of the reaction medium and instability or even inhibition of the activity of methanogenic microorganisms (Barber, 2005; Ganidi *et al.*, 2011).

3.3.5. Influence of the proportion between substrate and inoculum on the reaction

The hydrolytic stage is commonly reported in the literature as an inhibiting stage of AD, all due to the fact that the initial activity of microorganisms reflects the adaptation to culture in the environment, the conditions of the environment and the availability of substrate and nutrients necessary to promote the production of new cells, comprising the lag phase in the microbiological growth cycle, which delay the start of the process. However, the initial rate of biodegradation can be improved by using an inoculum (I) that comprises good nutritional loads. Yoon *et al.* (2014) and Gundoshmian and Ahmadi-Pirlou (2022) mention that the S/I ratio is obtained from the ratio of volatile solids (VS) content present in the substrate by the VS content or volatile solids suspended (VSS) content of the inoculum. Commonly, the inoculum is the product already biodigested, with high methanogenic loads present and the introduction of this in the system in different proportions can supply the deficiencies of the substrate (S).

To define an ideal relationship between S/I can be given through biomethanization potential tests (BMP) of organic matter or also by the methanogenic activity test (AME). Holliger *et at*. (2016), Caillet *et al.* (2019), Mansour *et al.* (2022) still mention the following characterization: easily degradable substrates tend to have a rapid production of volatile fatty acids (GVA), which can cause the souring of the biodigestate, it is necessary to establish a ratio of inoculum quantity is higher than that of substrate, in proportion to the proportion in which I/S is greater than or equal to 4 or S/I=0.25. For substrates that have a higher recalcitrant composition, there is the suggestion of addressing a proportion in which I/S is less than or equal to 1 or S/I=1.

3.3.6. Challenges in applicability

What has been commonly evidenced by the literature in recent years are experiences of applications of installation of biogas plants in small to large scale in a context of home/rural to industrial applicability, with the aim of using the OSW and reducing energy costs from the use of biogas as a renewable source. However, there is still a great challenge in defining models of reactors that have the ideal production of biogas, especially in a large-scale context of operation. Kacprzak *et al.* (2010), Hubenov *et al.* (2015), Ghosh *et al.* (2020a) mentioned that reactors operating in a single stage present difficulties in the productive yield of biogas due to the fact that the four stages of AD occur simultaneously in the same space, making it difficult to control metabolic, nutritional and operational properties.

Authors Nasr *et al.* (2012), Montgomery and Bochmann (2014) reported that reactors operating in two stages, in acid and methanogenic phase, may have better yields in methane production, shorter retention times and greater control of operational parameters, but costs may be higher.

Other factors that also impose the dissemination of AD for biogas production from OSW are closely associated with the lack of incentives on the part of local governments in the granting of financing, research and subsidies that integrate economic, social and environmental interests in a context of small and large companies, whether in the context of home/rural to industrial. Ghosh *et al.* (2020b) also reported that inadequate management of OSW is generally neglected in growing countries, making it difficult to use as substrate in biogas production plants.

4. CONCLUSIONS

The increasing participation of biomass in the current energy scenario strengthens the perception of sustainability due to the reduction of negative environmental impacts associated with the use of fossil fuels, especially if the biomass used comes from the energy recovery of organic solid waste (OSW). This recovery is favored by Anaerobic Digestion, having as its main product biogas, an important contributor in the electrical matrix in several countries, such as Germany, United States, China, Brazil and others. In this context, the scientific community has a challenging role to contribute in relation to biochemical, microbiological and engineering studies for the dissemination of Anaerobic Digestion as a biological treatment technology for organic solid waste, and local governments should have an intensified participation in the provision of financial and technological subsidies for the development of research in the energy sectors, engineering and environment, for the application of such large-scale treatment technology.

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