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Environmental factors and reactor configurations in biogas production from anaerobic co-digestion of fruit wastes

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Abstract— *A search for alternatives economically viable and environmentally sound to the world energy demand, stimulated the research in the field of anaerobic digestion, as a form of renewable energy and the anaerobic co-digestion is an alternative to use different types of residues, including food wastes. Therefore, this article presents an analysis of the scientific advances realized of the period of 2015 to 2018 in terms of anaerobic co-digestion, with emphasis on the use of different food residues, especially fruit and vegetable wastes, a different configuration of reactors, and kind of operational conditions used. A description of environmental factors affecting the process efficiency and the biogas generation based on substrate characteristics is presented in this review since these factors play an important role in the biogas yield and determine the metabolic conditions of the microorganism growth. Therefore, research should focus on the anaerobic digestion process balance, to identify optimal operating conditions through the use and valorization of wastes.*

Keywords— ***Anaerobic co-digestion, Biogas, Food wastes, Fruit waste, Methane.***

I. INTRODUCTION

One of the biggest environmental global problems is food waste (FW) production, which can be defined as the mass of food lost or wasted during the part of the food supply chains. According to estimates by FAO (2012), 28% of the world's agricultural area is used annually to produce food. Of this amount, 1.3 billion tons of fresh vegetables, fruits, meat, bakery, and dairy products are lost per year. This waste of food has unfavorable economic and environmental implications because represents around USD 990 billion per year, consumes 1/4 of all water used for agricultural purposes, and contributes with 8% in the emission of greenhouse gases [1, 2, 3, 4, 5].

Experts estimate that the production of FW is expected to increase by 44% until the year 2025. India ranks seventh in overall food wastage, while the Russian Federation tops the list. In China, the production of FW reached 97.7 million tons in 2017. In Europe, this raise is expected to be about 42% from 2006 to 2020, with the production of 126 million tons. The generation of FW has been noted in England with an amount of 14.257 million tons from 2009 to 2013. Germany generated about 12.258 million tons in the same period [1, 4, 6, 7, 8, 9, 10].

Food waste is organic materials constituted mainly by carbohydrates, proteins, lipids, and others traces of inorganic compounds, which can be degraded by microorganisms in an oxygen-free environment. This complex biologic treatment process performed in the absence of oxygen is called Anaerobic Digestion (AD), which is produced biogas while stabilizing the organic matter according to [2], [5], [7], [11], [12] and [13]. According to [14] each kilogram of food waste can generate approximately 0.1 m^3 of methane gas. Therefore, methane has a high calorific value of 17 to 25 MJ/m^3, which can be converted into energy. Estimates presented by [15] pointed out that just 15% of this gas is captured for beneficial use or flaring and the remainder converts into fugitive greenhouse gas emission from landfilling of food waste, that could amount to 3.1 gigatons CO_2-eq year^{-1} considering the total global of 1.6 gigatons of food waste each year.

The use of AD for treating food waste is attractive for some economic and environmental reasons, among them: (i) reduces the volume of material to be disposed of; (ii) avoids soil and water pollution; (iii) provides renewable and inexpensive energy. Therefore, the anaerobic digestion of solid wastes, such as fruits and vegetable wastes (FVW) present two important advantages, as treats the residues and simultaneously produces biogas [16]; [17]. However, this process is strongly dependent on environmental conditions such as pH, temperature, substrate typology, carbon/nitrogen/phosphorous ratio (C:N:P), particles size, presence of inhibitors, among others, that in certain unfavorable situations could cause instabilities in the process and consequently, impairing their performance [16, 18].

Co-digestion has been used to promote instantaneous digestion of two or more substrate and co-substrate mixtures, minimizing some imbalances in the process. Many researchers have been investigated co-digestion using various mixtures of industrial, farming, agricultural, and municipal waste materials according to [19] and [20]. So, this review, which cannot be exhaustive given the number of published papers about this theme, collected some papers published in the period of 2015-2018, to describe the trends for biogas from anaerobic co-digestion research, emphasizing different feedstocks, reactors, and operational conditions, that could significantly improve the biogas conversion.

II. METHODS

A summary of bioconversion of food waste into energy is presented including a brief description about energy demand with an emphasis on biogas, the anaerobic digestion process and the anaerobic co-digestion process, pointing the most used substrates, reactors and operating conditions nowadays. The literature used to compose the state of the art, the object of study of this review article, includes papers and scientific reports that have been obtained from scientific journals and online resources. To refine the search, the following keywords were used: anaerobic co-digestion, fruit residues, and methane. Due to the high number of articles published, only articles published in the period from 2015 to 2018 were considered.

III. FROM FOOD WASTE GENERATION TO ENERGY RECOVERY

According to the data presented by [21], approximately 1.3 billion tons of food is lost or wasted in the food supply chain. According to the researchers [2], [3], [5], [9], [22], [23], and [24], this food waste must increase in the coming decades, causing socio-economic and environmental problems. Fig. 1 shows an estimate of food waste in several countries as reported by these authors. The loss or waste of 1.3 billion tons of food also results in the waste of natural resources such as soil, water, and energy.

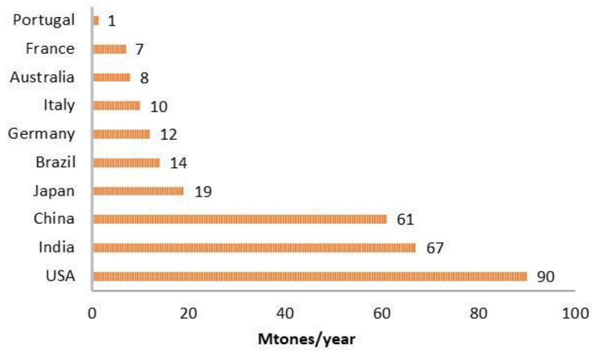

Fig.1: Food waste generation in some countries in 2017.

Estimates predict that 2.2 billion tons of food waste will be generated, as mentioned by according Food and Agriculture Organization (FAO), this would imply a total cost of approximately US$ 310 billion for low-income countries and US$ 680 billion for developed countries [7, 23, 25]. [2], [3], [5], [23] and [26] evinced that food waste cost around US$ 990 billion annually besides consuming a quarter of all the water used for agriculture purposes and contributed around 8% of total anthropogenic global greenhouse gas emission, accumulating annually 3.3 billion tons of CO_2 into the atmosphere.

The amount of fruit and vegetable represents 44% of the food waste contributor, and of this total, 25-30% are in the form of pomace, peels, and seeds [27]. According to [26] and [28], the number of food wastes in developed and low-income countries is in the range of 670 and 630 million tons, respectively. However, developed countries are produced 257 kg year^{-1} compared to 157 kg year^{-1} in low-income countries, on a per capita basis.

The bioconversion process is a method to minimize easily biodegradable biomass, due to its high moisture content characteristics, and realize bioenergy recovery simultaneously [22, 24]. From this precept, the use of an anaerobic process will promote effective and environmental-friendly treatment of this type of waste and its valorization in the form of others products, such as methane and hydrogen [1, 29]. Considering the importance of the AD process in the decomposition of organic materials, such as FVW, the next section presents a review of the principles that involve anaerobic digestion.

IV. ANAEROBIC DIGESTION: THE PROCESS AND RELEVANT FACTORS AFFECTING

Anaerobic digestion (AD) is the biological degradation process of organic substrates in the absence of oxygen, applied for stabilizing the organic matter. The application of this process is attractive for economic and environmental reasons because this consolidated technology reduces the material volume to be disposed of, prevents soil and groundwater pollution, besides provides renewable energy, e.g. biogas. However, is a complex process that involves a consortium of bacteria and methanogenic archaea, which needs control of some environmental factors [16, 30, 31]. Around 1870, Jean-Louis Mouras developed the first septic tank, introducing the concept of anaerobic digestion [32]. Biogas was reported for the first time by Louis Pasteur who stated that this could be used as energy. During the petroleum crisis, in 1970, biogas had its development peak. Since then, the application of this technology has been exploited for waste treatment and energy production [32].

Several authors have reported that AD is a biodegradation process of three or four steps including phases of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and for others, the acetogenesis is suppressed. The schematic of the four phases of the anaerobic digestion process is shown in Fig 2. However, irrespective of how many steps are involved in AD and defined by the researchers, it is known that the biodegradation process principles are similar and these steps are performed synergistically by several bacteria hydrolytic, acetogenic, hydrogen-producing, acetate-forming microbes, homoacetogens, methanogenic acetoclastic arches and hydrogenoclastic methanogens arches [7, 30, 33, 34].

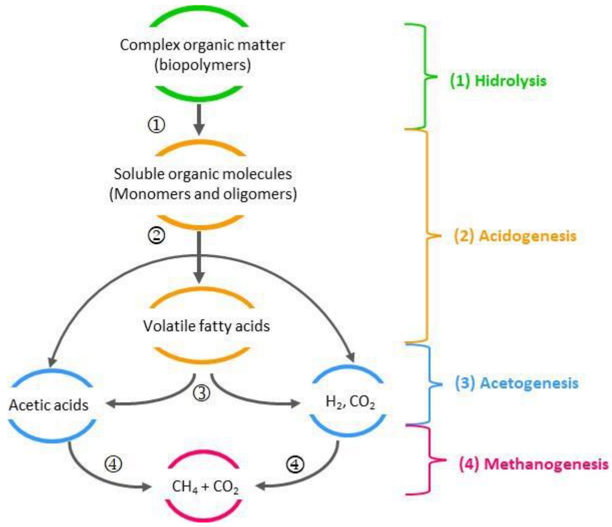

Fig.2: Schematic drawing of anaerobic digestion stages.

Environmental pollution and increase in energy demand are the greatest challenges to be faced by human beings in the coming years. One of the options currently studied is the use of biomass, which has shown to be a vast and promising source of energy [13]. The energetic usage of biomass can be enhanced by the AD, whose final product is biogas, rich in methane. The methane has a high calorific value of 17-25 MJ m^{-3}, which can be converted to energy (heat or electricity). So, the AD of organic wastes presents a double advantage, as it produces biogas and simultaneously treats the residues, reducing their disposal in sanitary landfills. Therefore, the extent to which this methane production efficiency becomes more developed and tested, allows this process to be commercially viable [14, 17]. However, to achieve this efficiency, the AD requires control of environmental conditions such as temperature, pH, alkalinity, carbon/nitrogen ratio (C/N), substrate typology, particles size, and organic loading rates (OLR) [16, 35]. Fig. 3 shows a summary of the operating conditions that allow biogas production in the anaerobic process.

4.1 Temperature

[11], [20], [36] and [37] point out that temperature is one of the most significant parameters affecting AD, especially in the enzymatic activity, thus influencing the biogas yield. Generally, anaerobic bacteria can grow at psychrophilic (10-30ºC), mesophilic (30-40ºC) and thermophilic (50-60ºC) conditions, however the mesophilic process is more stable if compared to the others and shows higher performance during the digestion process, that there is a greater microbial diversity in mesophilic conditions.

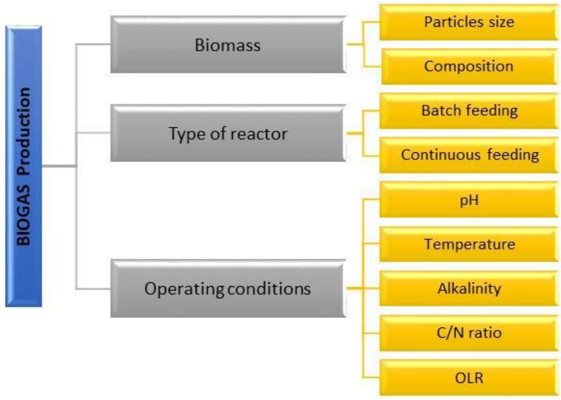

Fig.3: Operational control variables of the AD process.

These researches mentioned that in thermophilic conditions, there is an increase in AD performance and consequently of biogas production, due to the higher specific growth rates, higher metabolic rates, and higher destruction of pathogens. Despite this, there is a reduction in the methane content compromising the biogas quality by the decrease of the CO_2 solubility due to the increase in temperature. Therefore, it can be concluded that in mesophilic conditions (mainly in 32-35ºC) there is an improvement in the stability of the anaerobic digestion process, and can achieve better methane conversion.

4.2 pH value and alkalinity

When it comes to biological processes, pH is a limiting factor because influencing the ionized and non-ionized compounds forms, such as hydrogen sulfate, ammonium and other fatty acids, which are toxic to some microorganisms. On this control parameter, for AD process, the ideal range of pH is 6.8 to 7.3 [13, 20], that varies according to the microorganism's groups involved in each of the anaerobic digestion stages. For example, the optimum pH for fermentative bacteria that act on the hydrolysis and acidogenesis is between 5.5 and 6.5, while methanogens prefer a pH close to neutrality, since they are more sensitive to variations outside this range [13]. So, the anaerobic digestion, with focus in biogas production need to maintain a suitable pH range between 6.5 and 7.5 during the whole process, avoiding any sudden variation that may cause imbalance of the microorganism's metabolic functions involved [2, 30].

[14], [23] and [38] stated that alkalinity is another factor that can guarantee the stability of the pH, especially the variations that occur in the hydrolysis phase. According to [39], to ensure such stability, it is necessary to maintain the range of total alkalinity between 13,000 – 15,000 mg L^{-1} and volatile acids concentration below 1500 mg L^{-1} and the ratio intermediate alkalinity/partial alkalinity (IA/PA) equal or less than 0.3.

4.3 Carbon to Nitrogen (C/N) ratio

The performance of AD is significantly affected by C/N ratio and an optimum value is needed because anaerobic microorganisms require carbon as energy and nitrogen to form their cell proteins, i.e., an appropriate nutrient balance for their growth. This is the reason to maintain minimum levels of these nutrients in the medium and then guarantee microbial growth and performance because improper C/N ratios could result in high volatile fatty acids accumulation and/or high ammonia released, both of which are potential inhibitors and could cause the possible failure of the AD process [40].

Several researchers reported a wide range of C/N ratio, which is essential to reach an optimal biogas yield in the balance of sufficient nutrient supply [11, 30, 41]. The most recommended C/N ratio in the literature range from 20/1 to 30/1 for anaerobic bacterial growth; however, some authors point to an even lower range, such as 15-20/1, indicating that optimum C/N ratio depends on the characteristics of the substrates [11, 13, 16, 30, 42, 43].

4.4 Substrate characteristics

Another environmental factor that interferes in the anaerobic digestion process is the characteristic/ composition and size particles of the substrates [16, 44]. In the literature, this aspect has not yet been extensively treated and [45] mentioned that there are only a few studies that relate the impacts of the substrate on the anaerobic digestion process. However, the characteristics related to substrate composition in terms of carbohydrates, lipids, and proteins are key factors that influence the biological metabolism and consequently, in the performance of anaerobic digestion, because several substrates are more biodegradable while others more complex [39].

[36] affirm that a high concentration of substrate may become toxic to the agents responsible for anaerobic degradation, causing the accumulation of total ammonia (TAN), free ammonia (FAN), and volatile fatty acids (VFA). [46] identified an appropriate ratio of food waste/inoculum to maximize the methane production, with a buffered environment, avoiding low pH. [18] and [20] mentioned that particle size also influences the process since they observed that the smaller the surface area, the better the hydrolysis process because it facilitates the performance of the microorganisms.

4.5 Organic loading rate

The number of organic materials subjected to biological reaction in a certain time period, and per unit of reactor volume is called Organic loading rate (OLR). For many authors, this is the key that defines the balance between the acidogenesis and methanogenesis phases. Therefore, to provide a maximum biogas generation, the OLR is maintained at high loads in many experiments [36].

The principle governing the best OLR values are related to the reactor configuration and the composition of substrates used. [47] reported a decrease of the volatile acids when the OLR was increased, and consequently the hydrolysis rate was reduced in the anaerobic digestion of food waste. According to [20] and [47], the OLR must be controlled as an environmental condition that interferes in the anaerobic digestion process and the range of optimum values of OLR must be calculated for each bioreactor project, associated with the type of substrate. Therefore, a general optimum range cannot be mentioned for all bioreactors because it differs according to the substrate and inoculum.

V. ANAEROBIC CO-DIGESTION OF FRUIT AND VEGETABLE WASTES

At the end of the 1970s, anaerobic digestion underwent an adaptation, known as anaerobic co-digestion (AcoD) or co-fermentation, a process in which different mixed residues can be simultaneously digested, achieving yields equal to or even higher than the anaerobic digestion process. AcoD has shown advantages over AD because it provides greater balance in terms of nutrient availability, offers better buffering to the system, depending on the blend, and also dilutes certain inhibitory compounds [48].

The synergistic effects of AcoD were pointed by [1], [16], [17], [23], [38] and [49], when they mentioned the increase in the biodegradability, increase in the active biomass concentration as a function of the increase of the microbial community involved in the process, production of a digestate with improved characteristics to use in agriculture, suggesting that co-digestion process is a feasible option to overcome the mono-digestion limitations. There is an extensive variety of organic materials that can be used as feedstock to the anaerobic co-digestion and the scientific literature presents several results that indicated correlations between substrates used and biogas yield [44].

A series of researches and their respective data will be mentioned in sequence to present the main scientific results about anaerobic co-digestion, specifically of fruit and vegetable wastes, reported in the 2015 to 2018 period. A summary of several types of research, addressing different types of reactors, substrates, and inoculum is presented in Table 1.

[50] evaluated the effect of the addition of cow manure with straw in the single-phase and two-phase digestion of fruit and vegetable wastes (FVW) and concluded that the substitution of vegetable wastes with cow manure (CM) from 20 to 40% resulted in a methane yield decrease and reduction of both mono-digestion and co-digestion. However, when comparing the equivalent waste combinations, the authors verified that the yield was higher in single-phase process, with 33% (100% FVW), 40% (80% FVW / 20% CM) and 58% (60% FVW / 40% CM).

[51] studied the effect of waste-mixed sludge (WMS) co-digested with fruit and vegetable wastes (FVW) at different organic loading rates ranging from 1.46 kgVS m^3 day^{-1} to 2.8 kgVS m^3 day^{-1} during 280 days. The results indicated that the increase in OLR showed major benefits in comparison with the other conditions analyzed and also that co-digestion with FVW led to an increase in the amount of the biodegradable organic carbon in the digester, equalizing the typical high nitrogen concentration of WMS. Therefore, the net electrical energy available achieved a maximum value of about 3,500 MWh $year^{-1}$ when operated with to an OLR of 2.1 kgVS m^3 day^{-1} (i.e. 22 tonnes day^{-1} of FVW).

Anaerobic co-digestion of cow manure, with carbon slowly released from corn straw, as well as the effect of adding available carbon quickly released, with fruit and vegetable waste was explored by [52]. Two experiments were conducted consisting of group A (FVW dosage was 5% of cow manure) and group B (FVW dosage was 1%), and Group C used as the control. The authors verified that the hydrolysis process of the anaerobic co-digestion of the cow manure and corn straw was improved by adding the FVW. The specific methane yield increased from 202.06 to 522.92 mL gVS^{-1} in group A and 174.98 to 743.24 mL gVS^{-1} in group B.

Table 1: Some scientific works about anaerobic co-digestion of fruit and vegetable waste

Reference	Reactor	Substrates	Inoculum	Remark	Methane production/yield
[17]	Batches glass reactors	Organic fraction of municipal solid waste + FVW	Anaerobic sludge	This study investigated the digestion of four different organic fraction of municipal solid waste and fruit and vegetable waste ratios that was evaluated in terms of biogas and methane yield, TVS removal rate, and stability of the anaerobic process.	396.6 N mL g VS^{-1}
[49]	Continuous anaerobic digesters	Sewage sludge + three different fruit waste	Sludge from a stable lab-scale mesophilic digester	The transitory state was evaluated with two different conditions: co-substrate changing and co-substrate stopped.	1.1 L CH_4 L_R day^{-1}
[50]	Anaerobic reactor	Cow manure with straw + FVW	Granular sludge	The influence of different proportions of lignocellulosic substrate on the single-phase and two-phase digestion of a readily biodegradable substrate was investigated to determine the optimum co-substrate ratio and the process best suited for co-digestion.	82.3 L $week^{-1}$ (single-phase) 7 L $week^{-1}$ (two-phase)
[51]	Gas-tight anaerobic reactor	waste-mixed sludge + FVW	Not mentioned	The effect of waste-mixed sludge co-digested with fruit and vegetable waste was investigated at different organic loading rates.	900 NL m^3 day^{-1}
[52]	Continuous stirred tank reactor (CSTR)	Cow manure and corn straw + FVW	Not mentioned	In this study, the anaerobic co-digestion of cow manure with available carbon was investigated to measure the effect of adding available carbon quickly released, so the fruit and vegetable waste could be exploited as substrate.	202.06 mL g·VS^{-1} (group A) 174.98 mL g·VS^{-1} (group B) 165.08 mL g·VS^{-1} (group C)
[53]	Anaerobic batch reactors	FVW	Sewage sludge	The feasibility of fruit and vegetable wastes to yield methane gas has been evaluated by adopting the automatic methane potential test system and substrate/Inoculum ratio has also been optimized to get maximum methane gas.	265-444 N mL g VS^{-1}
[54]	Anaerobic batch reactor	FVW	Swine manure effluent + cattle manure and raw cattle manure	This research investigated the chemical composition influence of twelve different batches of fruit and vegetable waste with different compositions collected over one year, on the biochemical methane potential (BMP).	288 to 516 NL CH_4 kg VS^{-1}
[66]	Gas-tight	Waste-mixed	Not	The effects of anaerobic co-	435 NL CH_4 kg

	anaerobic reactor	sludge + FVW	mentioned	digestion of waste-mixed sludge with fruit and vegetable waste on the methane generation of a mesophilic digester was investigated.	VS^{-1}
[67]	Continuously stirred-tank anaerobic bioreactor	Swine manure + a mixture of FVW	Not mentioned	Various co-substrate ratios were investigated under mesophilic conditions in a pilot-scale continuously stirred-tank bioreactor of obtaining an optimal ratio for maximizing the methane production.	0.65 m^3 kg VS^{-1} day^{-1}
[68]	Gas-tight anaerobic reactor	Waste-mixed sludge + FVW	Not mentioned	The effect of WMS co-digested with fruit and vegetable waste was investigated at different organic loading rates.	900 NL m^3 day^{-1}
[69]	Anaerobic batch reactors	Mixture of cooked vegetables, rice, bread, cereals + fruits in semi-solid forms	Seed sludge	The optimum F/M ratio was evaluated and determined the optimum temperature for anaerobic digestion of food waste charged with total solids content of 25–50%.	0.88 L CH_4 g COD^{-1} (mesophilic) 0.62 L CH_4 g COD^{-1} (thermophilic) 0.73 L CH_4 g COD^{-1} (psychrophilic)
[70]	CSTR and UASB	Mixture of waste matter consisting of watermelon, apple + potato	Anaerobic sludge of wastewater treatment plant	Two-phase anaerobic digestion in acid reactor was investigated, with a completely stirred tank (CSTR) acid reactor and an up-flow anaerobic sludge bed (UASB) methane reactor to examine the lactate degradation.	261.4 mL g COD^{-1} removed
[71]	Discontinuous anaerobic digestion reactors	Seventeen types of fruit waste, including peels, seeds, and shells	Anaerobic sludge from Biogas plant fed with pig manure	Batch tests were realized to compare the AD performance of 17 types of fruit residues as a single substrate, as well investigated the characteristics of these fruit waste in methane yield, comparing different kinetic models.	383.4 mL g SV^{-1} (Rambutan seeds)
[72]	Batches glass reactors	Ripe banana + ripe longan + rambutan	Mixed sludge from two full scale anaerobic digesters	This study was divided into two main parts: Firstly, identify the bio methane potential of key tropical fruits waste. The second part was to evaluate an appropriate digestion strategy of the selected substrate (banana peel) in continuous anaerobic digestion systems.	330.6 mL CH_4 g VS^{-1} (ground banana peel) 268.3 6 mL CH_4 g VS^{-1} (chopped banana peel) 234.66 mL CH_4 g VS^{-1} (chopped longan waste)

[73]	Anaerobic co-digestion batch reactors	Empty fruit bunches + palm oil mill effluent + sewage sludge	Mesophilic methane production sludge	Empty fruit bunches, palm oil mill effluent, sewage chemical sludge and sewage biological sludge were evaluated for methane production under liquid-state anaerobic digestion and solid-state anaerobic digestion.	18 mL CH_4 g VS^{-1}
[74]	Semi-continuous bench scale stirred tank reactors	Poultry manure + FVW	Sludge from dairy effluents treatment anaerobic lagoon	The authors evaluated the performance of anaerobic digestion of poultry manure co-digested with fruit and vegetable waste, in terms of biogas production, organic matter reduction and release of nitrogen compounds.	0.21 NL CH_4 g VS^{-1}
[75]	Continuous stirred tank reactor (CSTR)	Peach waste + apple pulp waste	Sludge and granular sludge	This work had as objective to evaluated the performance of a two-stage anaerobic process and the optimal operational conditions, taking into account the degree of acidification and biomethane production under different operational conditions.	4.33 L CH_4 L day^{-1}
[76]	Glass bottles reactors	Durian shell + chicken manure + dairy manure + pig manure	Anaerobic sludge	Anaerobic co-digestion of Durian shell with chicken manure, dairy manure and pig manure at different ratios was performed to investigated the methane production and determined the principal synergistic effects of co-digestion.	224.8 mL g VS^{-1}
[77]	Anaerobic batch reactors	Sugarcane bagasse + FVW	Waste activated sludge	This research investigated the influence of mixture of waste activated sludge as inoculum to the ratio of sugarcane bagasse and fruit-vegetable waste as substrate, to evaluated the biogas yield during anaerobic co-digestion.	2600 mL day^{-1} (biogas yield)

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One research that sought to assess the feasibility of fruit and vegetable wastes to yield methane gas and substrate/inoculum (S/I) ratio was conducted by [53]. Methane potential obtained from the fruit waste was 0.444, 415.12, 358.27, 337.31 and 265.03 N mL gVS^{-1} to S/I ratio of 0.43, 0.67, 1.0, 1.5 and 2.3, respectively, whereas, this potential from vegetable waste was 470.91, 435.47, 403.46, 351.42 and 247.97 N mL gVS^{-1} to S/I ratio of 0.43, 0.67, 1.0, 1.5 and 2.3, respectively. According to these authors, the S-shaped cumulative methane curve indicated the lower production of methane at the highest S/I ratio, that is, as lower inoculation lower is the microbial activity and more risk of inhibition of the anaerobic digestion process.

Twelve different batches of fruit and vegetable wastes were used by [54] to investigate the influence of chemical composition on the biochemical methane potential (BMP). The authors verified that BMP ranged from 288 to 516 LN CH_4 $kgVS^{-1}$, with an average of 377 (67) LN CH_4 $kgVS^{-1}$ and 79% of biodegradability, and attributed this variation to the chemical composition over time. Moreover, they also developed statistical models by multiple linear regression to predict methane potential and affirmed that the best BMP prediction was obtained using the model including lipid, protein, cellulose, lignin, and high calorific value, with an R2 of 92.5%. The authors concluded that the high calorific value might be useful for predicting the BMP.

When analyzing the data presented in Table 1, it is understood that for each combination of substrate used, the AcoD process must be differently designed to obtain the optimal treatment efficiency. However, scientific research has indicated the feasibility of the AcoD process has been increasing, and that there is an even greater potential for biogas production using co-digestion of different feedstock wastes. Among the challenges of maintaining the AcoD process are the biogas yield rate, the substrates ratio, process stability, and nutritional balance, which require more investigation.

Various strategies have been applied to improve the biogas production from anaerobic co-digestion of food wastes, especially of fruits and vegetables, and different improving effectiveness has been reported in the scientific literature. However, these strategies cannot be compared directly with each other about their effectiveness, because operational conditions are different from each other. Thus, because it is a complex process, the efficient results of anaerobic digestion are directly related to the interaction of some factors, among them: applied organic load, operational conditions, and configuration of the reactors.

VI. REACTORS CONFIGURATION AND FLOW MODE

The anaerobic digestion system can be classified according to the substrate type, temperature, or power supply. [55] suggested three types of classification: (A) total solids: wet type (with < 10% total solids TS) or dry type (> 20% TS); (B) temperature: mesophilic (35-40°C) or thermophilic (> 55°C) and (C) reactor feeding mode: batch fed; semi-continuously fed or continuously fed. The anaerobic digestion process can occur in different types of reactors, regardless of their classification, so in this section are described some types of reactors most commonly used in scientific experiments and their results in the anaerobic co-digestion process for biogas production. Thus, this section was divided into two topics: batch and continuous reactors.

6.1 Flow mode of reactors in anaerobic co-digestion

6.1.1 Batch reactors

For [56] the most common anaerobic reactor is the anaerobic sequential batch reactor (ASBR), characterized by a single-tank unit in which occur all of the treatment steps and processes. This reactor presents some advantages such as operational simplicity, effluent quality control, fewer maintenance requirements, low cost, and high biogas yield.

[57] operated a batch reactor to investigate the synergistic effects of mono and co-digestion of six different ratios of food wastes (FW) and pig manure (PM) on the specific methane yield (SMY) and reaction kinetics. Lower average daily methane yield was observed in the PM mono-digestion (260 ± 13 $mLCH_4$ gVS^{-1}) than in the food waste mono-digestion (516 ± 33 mL CH_4 gVS^{-1}), with highest value of 521 ± 29 mL CH_4 gVS^{-1} to PM/FW mixing ratio of 1/4. The authors affirmed that the methane generation increased when combining PM and FW due to the synergistic effects of using two substrates.

[58] developed a compact three-stage anaerobic digester (TSAD) for food waste substrate composed of three separate chambers in a single-stage digester. TSAD achieved a higher methane yield of 24–54% with the production of 0.307 LCH_4 gVS^{-1} when compared to traditional reactors of one-stage (0.199 LCH_4 gVS^{-1}) and two-stage anaerobic digesters (0.249 LCH_4 gVS^{-1}).

To treat food waste at mesophilic conditions, [59] used a digester system consisting of three reactors operated in single and two-phase mode. Two-phase mesophilic digestion presented higher methane production (446 LCH_4 $kgVS^{-1}$) when compared to the single-stage operation (380 LCH_4 $kgVS^{-1}$). The authors concluded that although it is more complex, the reactor operated in two-phase mode has the potential to maintain the process in periods of low rate.

[23] also affirmed that two-stage AcoD is more effective if compared to the conventional single-stage, because it can improve the degradation rates, methane yield, i.e., the overall process efficiency.

6.1.2 Continuous reactors

[60] investigated the performance of a continuous flow reactor, operated at 37ºC, in the anaerobic co-digestion of food waste with high solids content. The reactor was submitted to different organic loading rates of 5, 6, and 9 kgVS m^3 d^{-1}, corresponding to the hydraulic retention time of 26, 25, and 14 days, respectively. The authors reported that the daily biogas production drastically decreased from 196 to 136 L d^{-1} when the organic loading rate was increased from 6 to 9 kgVS m^3 d^{-1}. They concluded that the increase in the organic loading rate, and consequently decrease of hydraulic retention time, contributed to the reduction in the efficiency and instability of the process.

To evaluate the effectiveness of the anaerobic co-digestion of food wastes (FW) and de-oiled grease trap wastes (GTW) in the biogas production, [61] operated three different systems - a lab-scale mesophilic digester (MD), a temperature-phased anaerobic digester (TPAD) and a TPAD with recycling (TPAD-R). Each reactor consisted of a continuous stirred tank reactor with temperature control and biogas collection and was operated under mono-digestion (FW) and co-digestion (FW + de-oiled GTW), synchronously. The authors reported greater biogas yields to mono-digestion in MD (19%) and TPAD-R (19%) than to TPAD (8%), with the maximum value of 0.62 L gVS^{-1} in the lab-scale mesophilic digester (MD) of the co-digestion system.

A two-stage anaerobic system, coupled in continuously stirred tank reactor (CSTR) and sequential batch anaerobic reactor (ASBR) was assembled by [62] to investigate the anaerobic co-digestion of fruit and vegetable wastes (FVW), waste-activated sludge (WAS), olive mill wastewater (OMW) and cattle manure (CM). The results showed that the single-stage digester was characterized by higher electric and thermic energy productions, with methane yield around 340 L $kgVS^{-1}$. However, there was an increase in the energy production associated with the two-stage system when increasing gradually the OLR and biogas recirculation. The authors verified 1765.2 kWh $tonVS^{-1}$ of electrical energy and 2942.1 kWh $tonVS^{-1}$ of thermal energy when applied OLR of 3.44 kgVS m^3 d^{-1}, and assumed that two-stage anaerobic co-digestion may be a mechanism used in pollution control and bioenergy recovery from organic wastes, including fruit and vegetable wastes as substrate.

In another study, [63] compared the performance of single and two-stage anaerobic digestion processes using food waste as substrate. CSTRs reactors were used for a one-stage process (230 L) and a two-stage system with two reactors (200 and 760 L), operated in thermophilic conditions. The results proved that the systems showed high biogas yields. The specific gas production was higher in the two-phase system with 0.88 m3 biogas $kgVS^{-1}$ than in the one-phase system with 0.75 m3 biogas $kgVS^{-1}$. The authors concluded that the methanogenic process was positively affected by the two-phase process.

6.1.3 Semi-continuous reactors

[64] studied the methane production capacity in mesophilic conditions (35ºC) treating food waste in a semi-pilot batch reactor (6 L) and pilot-scale semi-continuous reactor (300 L). The substrates used were composed of vegetable waste and pesto sauce and other kinds of sauces wastes. Already pilot-scale test (semi-continuous mode) involved only the vegetable mix waste (VMW) because of its higher heterogeneity. The results of the semi-pilot scale (five replicates) indicated biogas and methane specific production of 0.554 Nm^3 $kgVS^{-1}$ and 0.294 Nm^3CH_4 $kgVS^{-1}$, respectively. The results of biogas daily production ranged from 50 NL d^{-1} to 100 NL d^{-1} in the pilot-scale test. The higher methane specific production was obtained in the semi-continuous test with values 76% higher than those obtained in the batch test. Another important result indicated that the average methane content was 20% greater on the pilot scale than on the semi-pilot scale.

[65] evaluated the impact of digesting fruit and vegetable wastes (single substrate) at different ratios to achieve the optimal mix in a two-stage semi-continuous digester composed of a hydrolysis unit (6 L, first stage) and a vertical continuously stirred digester (35 L, second stage), both operated at 35º C. The results revealed that the biogas yield increased proportionally with the OLR. However, when the OLR exceed 3.4 kg VS m^{-3} d^{-1}, a decline in biogas yield was observed. Optimal conditions were found to the OLR range of 2.68-2.97 kg VS m^{-3} d^{-1}, resulting in a biogas yield between 2.4 and 2.8 Nm^3biogas m^{-3}reactor d^{-1}. The average specific biogas and methane were 0.87 Nm^3 $kgVS^{-1}$ and 0.49 Nm^3 $kgVS^{-1}$ at the optimal conditions, respectively.

VII. CONCLUSION

This paper described researches about the development on the anaerobic co-digestion (AcoD) process of fruit and vegetable wastes as substrates, published in the period from 2015 to 2018. From the data reported in several studies, it can be concluded that the AcoD process from different biodegradable organic materials is a technology economically and environmentally feasible to biogas generation at both the laboratory scale and the industrial scale. However, some challenges still have to be overcome, among them the characterization of the different organic materials and the process parameters, and the behavior of microorganisms to ensure maximum process efficiency. A comprehensive analysis to combine strategies to improve the co-digestion process is still a task for the scientific field, especially to optimize the operation of anaerobic reactors for the sustainable conversion of organic waste to sustainable bioenergy.

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