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Anaerobic Digestion for Agro-industrial Wastes: a Latin American perspective

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***Abstract*— The main aspects of the anaerobic digestion process are reviewed. The characteristics of the more important systems for the treatment of liquid and solid wastes are presented. High rate reactors for the treatment of liquid wastes such as the UASB (Up-flow Anaerobic Sludge Blanquet), EGSB (Expanded Granular Sludge Bed) and IC (Internal Circulation) reactors are described. Additionally, different types of solid waste digesters are discussed. The valorization of wastes as a source of energy that contributes to minimization of the carbon footprint is highlighted. Additionally, the use of digestate as soil amendment and nutrient addition contributes to the environmental use of resources. Data related to the methane yield for different substrates are collected, and the potential of methane generation when the waste quantities are known is computed. Estimations from Latin-American countries and outside the region are reviewed to evaluate the impact on the energy demand.**

***Index Terms*— Biogas, Methane, Energy, Reactors**.

I. INTRODUCTION

A. *Evolution of the anaerobic digestion*

The use of anaerobic microorganisms for waste treatment has been described for more than hundred years [1]. At the end of the 19th century, the first hybrid reactors that included a filter and the Imhoff tanks were developed. Imhoff tanks were conceived both as settler and digester, but there was no complete solution for the treatment of wastewaters. In contrast, in the mid-20th century, the aerobic technology for wastewater treatment was consolidated. At that time, anaerobic technology was used to treat aerobically generated sludges. In the 1960s, Young and McCarty (1969) [2] published studies using anaerobic filters. More than a decade later, Gatze Lettinga introduced a novel concept for anaerobic reactors: the Up-flow Anaerobic Sludge Bed (UASB) [3]. From there, the anaerobic treatment of effluents was extensively applied worldwide. Currently, anaerobic technology is considered to be consolidated, even if more research and development are needed [4 - 5].

Solid and liquid waste treatments are usually performed to prevent contamination; however, when wastes with a high organic content are treated using anaerobic processes, another goal could be accomplished: energy generation. Currently, changes at the global level (greenhouse emissions and energy crisis) have led to encouragement for renewable energies and biotechnological developments, so a new economy based on environmental and energetic factors is being established [6]. In this sense, concepts such as bio-refinery are being adopted based on the biotechnological transformation of biomass including energy generation [5, 7 – 10]. From this point of view, anaerobic technology is considered to be more efficient regarding greenhouse emissions [11] and can compete with other biofuels [12]. In this scenario, anaerobic digestion plays a key role because the products generated at different metabolic stages (hydrogen and methane) can be used as energy sources, including in boilers, in internal combustion engines or in fuel cells [13]. Other metabolic products, such as volatile fatty acids (VFA), could be used as raw material for additional transformations: methane, biopolymers or other organic compounds.

B. *Process fundamentals*

Many interrelated processes involving different microorganisms are employed during the transformation of organic matter by anaerobic digestion. To degrade the organic matter to methane and carbonic anhydride, the biological reactions implicated must be integrated. Larger molecules are hydrolyzed to smaller ones (sugars, lipids and proteins) by extracellular enzymes, and these molecules are converted by intracellular enzymes to volatile fatty acids (VFA), hydrogen and carbon dioxide. Finally, methane is formed from acetate or from carbon dioxide and hydrogen by methanogenic archeas. The process could also be driven towards hydrogen production. To optimize the processes, the conditions must be adjusted for each particular substrate. In addition to the need for balance between the involved microbial populations, there are symbiotic relationships between certain groups of microorganisms that must be present for the proper performance of the process. Usually, methanogenesis is the rate-limiting step.

Solid waste treatment differs from liquid waste treatment because solubilization and hydrolysis of particulate material could be the limiting step of the process. Additionally, waste mixing must be properly performed to improve mass transfer phenomena and provide the adequate contact between the biomass and the substrate. Given that microorganisms cannot be separated from the solid wastes to be degraded, the retention time in the solid wastes digester is usually between 15 and 60 days; otherwise, the wash out of microorganisms occurs. In contrast, in the high rate wastewater reactor treatment, microorganism retention can be decoupled from liquid retention; then, the hydraulic retention time can be reduced to a few hours.

Currently, hydrogen production is a challenge for clean energy production. Nevertheless, studies are required to determine the stable performance conditions. When hydrogen production is pursued, due to thermodynamic restrictions, a substantial amount of organic matter remains in the waste and thus requires additional treatment [14 – 15]. When treating the remaining COD anaerobically, the net energy produced

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(hydrogen plus methane) is not much higher than that produced with exclusive methanation. Nevertheless, some advantages of hydrogen production must be addressed: because water is produced when combusting, hydrogen is an attractive clean fuel, and hydrogen can be obtained from other sources, providing versatility to the market concerning hydrogen generation. As a consequence, research on hydrogen production must be focused on obtaining a stable process.

II. LIQUID WASTE TREATMENTS

A. *Background*

The main anaerobic treatment systems include the following: lagoons, contact reactors, UASB, anaerobic filters, hybrid reactors, fluidized beds, expanded granular sludge bed (EGSB) reactors and internal circulation (IC) reactors.

With the UASB reactor conception by Gatze Lettinga in the 1980s, decoupling between the hydraulic retention time (HRT) and the biomass retention time (BRT) was achieved. Therefore, HRT could be decreased, and consequently, the reactor volume was diminished. Then, lower investment and operating costs were achieved, and more stable configurations were obtained. The decoupling between the HRT and the BRT was possible due to the good settlement properties of the sludge, which often occurred due to granule formation. Nevertheless, non-granular sludge with flocculent characteristics and good settlement properties has also demonstrated good performance in UASB reactors.

Later, based on the same concept, EGSB and IC reactors were developed. These reactors worked at higher volumetric organic loads and allowed lower volumes than UASB reactors. Their main differences from UASB reactors are as follows: high up-flow velocities (achieved by imposing external or internal recirculation) and higher height versus diameter ratios than UASB reactors.

B. *Low organic load systems*

Anaerobic lagoons: These extensive systems are applied in countries with land availability, and lagoons have low control requirements but usually organic matter removal efficiencies are low. Currently, it is customary to cover the entire surface of the lagoon to prevent greenhouse gas emissions and recover biogas energy. The HRT is between 10 and 90 days, the depth is approximately 6 m, the organic load applied is between 0.5 and 2 kgCOD m^{-3} d^{-1} and the removal efficiency is between 30 and 80%. Sludge purge must be performed every two to five years. Covered lagoons are an interesting option for existing plants based on extensive treatments, because biogas is captured and could be used for energetic purposes. However, operational problems like fatty material accumulation and low biodegradation rate due to low degree of mixing are presented [16].

Contact systems: These are robust reactors that are composed of an anaerobic stirred tank and an external settler to separate the sludge from the treated effluent. In this way, the HRT and BRT can be managed. Usually, a degasser is included to prevent sludge flotation due to the gas content. The organic loads are usually less than 5 kgCOD m^{-3} d^{-1} [17].

Anaerobic filters: Total or partial (hybrid reactors) are filled with a packing material that could proceed from different sources. The biomass grows fixed to packing, thus avoiding the washout of the microorganisms. Packing has a specific area of approximately100 m^2 m^{-3}, HRT is approximately 12 h, and organic loads of up to 4 kgCOD m^{-3} d^{-1} are achieved [18].

C. *Up- flow Anaerobic Sludge Bed reactors (UASB)*

UASB are compact systems with low area requirements, low operational and investment costs, low energy consumption and low sludge production. The UASB reactors are continuously fed from the bottom, which produces an up-flow stream towards the upper outlet. The up-flow stream passes through the sludge bed composed of the aggregates of microorganisms and granular or flocculent biomass. The up-flow stream and gas production must provide sufficient mixing to ensure the proper contact between biomass and substrate. Because the aggregates have good settlement properties, the time that sludge is retained in the reactor is higher than the retention time of the liquid phase. Then, methanogenic microorganisms that have slow growth are not washed out. In the upper part, a three-phase separation system allows for the exit of the gas and liquid and for the return of sludge that eventually could reach the top of the reactor. The three-phase separator must be designed to capture the generated gas and the liquid flow exiting from the reactor, according to the parameters established for the regular operation of the system. Concerning the sludge return, the linear velocities in the settlement zone must be according to the settlement properties of the sludge.

The Biochemical Oxygen Demand (BOD_5) and the Chemical Oxygen Demand (COD) removal efficiencies are approximately 75 and 65%, respectively. Additionally, the sludge is usually generated with a relatively high concentration and a good dehydration capacity. Although the acclimation of sludge is required for the start-up, reactor performance can be resumed after long periods of interrupted functioning.

Some weaknesses should be addressed: odors occasionally occur due to the incorrect design or construction of the gas collection system, low tolerance to toxic loads exists, post-treatment is always required and longer start-up periods than aerobic systems are required

D. *Expanded Granular Sludge Bed reactors (EGSB) and Internal Circulation reactors (IC)*

There is a new generation of anaerobic reactors that improves the UASB concepts. The EGSB and IC reactors work like fluidized beds, due to the high up-flow velocities applied. This flow is produced by an external recirculation in the EGSB and using a gas-lift effect in the IC. The biomass must have excellent settlement properties to prevent wash out. Table 1 shows organics loads and other design characteristics of the three types of reactors.

Table 1. Organic loads and design parameters of UASB, IC and EGSB reactors.

Reactor	Up-flow velocity ($m\ h^{-1}$)	Height/Diameter ratio	Organic load (kgCOD m^{-3} d^{-1})
UASB	0.5 – 1.0	0.2 – 0.5	10 – 20
EGSB	10 -15	4 -5	20 – 40
IC	10 – 30 ^{a} 4 – 8 ^{b}	3 -6	20 - 40

a: in the upper part of the reactor; b: in the lower part

E. Main types of liquid wastes

Anaerobic digestion can be applied to many of the liquid wastes generated in the agroindustry: malting, brewery, soft drinks, distillery, pulp and paper, food industry, pharmaceutical, yeast, and leachate [19 – 21]. Next, the most relevant wastewaters in the region are addressed.

Slaughterhouse industry **-** The origins of slaughterhouse wastewater are in the following processes: bleeding, deboning, evisceration, and washing. Three types of effluents are produced: red water, green water and sewage. The red water is mainly generated in the slaughter operations and mainly contains lipid and protein material. The green water is derived from evisceration processes and washing and has high content of lignocellulosic solids and fats. Sewage is derived from toilets for workers. The mixture of the different streams generates a complex effluent that contains proteins, fats and lignocellulosic materials both in a soluble form and in a suspended solids form. Table 2 shows a typical characterization of the slaughterhouse wastewater from a typical factory.

Table 2. Slaughterhouse wastewater characterization.

Parameter	**Red water**	**Green water**	**Sewage**
Flow (m^3 d^{-1})	1900	800	200
Temperature (ºC)	29	23	20
total COD (mg L^{-1})	6700	21000	730
Soluble COD (mg L^{-1})	2400	3600	550
TSS (mg L^{-1})	1900	12000	400
VSS (mg L^{-1})	1600	10000	200
Oil & Grease (mg L^{-1})	1200	1700	10
COD/NTK	25	40	8
COD/P	390	310	150
pH	6.5	7.5	7.5

Considering the effluent flows and the volume of slaughter, an average load of 23 kg COD per ton of slaughtered animal is obtained.

Milk industry **-** The effluents from the milk industry are primarily generated during cleaning procedures, where alkalis and acids are used in addition to water and detergents. Thus, the effluent presents milk residues in addition to the products used for cleaning. There are several reports concerning the malfunctioning of UASB reactors when treating milk effluents. This malfunction is usually linked to the fat content of the effluent that is approximately 40% of the organic. This material is floated by the biogas bubbles and is accumulated below the biogas collecting device, thereby preventing biogas release. Additionally, the dispersed growth of biomass was reported in UASB reactors treating milk effluents, which produced poor settlement properties and consequently biomass wash-out. Additionally, fat adsorption onto the biomass surface prevents proper substrate-microorganisms contact. Thus, a modified system was developed in Uruguay [22]. This system has been successfully working in a full-scale plant because 2005 [23]. The UASB concept was modified by including the following: 1) a fat extracting device at the top of the reactor, 2) an external settler, to return biomass escaping with the effluent, and 3) a biodigester, to stabilize the extracted floated material, which once stabilized is returned to the modified UASB reactor. In table 3, the characteristics of milk effluents in Uruguay are presented.

Table 3. Mean values for the Uruguayan dairy industry wastewater.

2.7 $m^3_{wastewater}$ m^{-3}_{milk}

9.7 kg COD m^{-3}_{milk}

3.6 kg COD $m^{-3}_{wastewater}$

2.0 kg BOD_5 $m^{-3}_{wastewater}$

0.49 kg O&G $m^{-3}_{wastewater}$

Additionally, some industries produce cheese whey, and beyond being used for animal food, whey is often a residue with high COD concentration (approximately 60 gCOD L^{-1}). Because of this high concentration and because it is usually not a waste stream, the whey must not be treated in dairy wastewater treatment units. The preferred option when whey is considered waste is to treat it in a solids digester.

Bioethanol distillery vinasse **-** During alcohol production from sugar cane, a liquid waste called vinasse is produced. Between 13 to 15 liters of vinasse are generated per liter of alcohol [24 – 25]. The amount of organic matter present in the vinasse depends on the distillation process and the raw material used [26]. Starting from cane juice, values between 20 and 33 gCOD L^{-1} are reported, whereas starting from molasses, the values are between 48 and 120 gCOD L^{-1} Additionally, the reported values of the biodegradable fraction are highly variable. Therefore, the characterization of the effluent is required for the proper design and subsequent operation of the treatment system. The following challenges are marked by Moraes et al. (2015) [10] for the biogas production from ethanol vinasse in Brazil: i) current feasibility of disposing of vinasse *in natura* in surgarcane cultivation (fertirrigation); ii) predominance of empirical approaches in the fundamental studies of anaerobic digestion of vinasse; iii) unsatisfactory results obtained in the few full-scale anaerobic reactor plants; iv) lack of valorization of biogas as an alternative energy source.

III. SOLID WASTE TREATMENTS

A. Background

In the anaerobic degradation of solid wastes, the microbiological processes are the same that are involved in the degradation of liquid wastes. The major difference between liquid and solid waste treatment is the impossibility of separating the substrate and the microorganisms in the latter. In fact, a great improvement in liquid treatment was accomplished when separation of HRT and BRT was achieved; in solid treatments, this is not possible. Therefore, the solid treatments require larger residence times and consequently larger volumes. Because the residence time for substrate and microorganisms is the same and considering that the methanogenic microorganisms have slow growing rates, residence times between 15 and 60 days are required to avoid biomass loss. Additionally, the hydrolytic step could be the rate-limiting step, and effective mixing conditions must be provided to achieve good contact between the substrate and exoenzymes.

B. *Substrate types*

The main agroindustrial wastes are presented in table 4, and the biomethane potential yield is reported.

Table 4 Review of methane yield for different kinds of substrates from agroindustrial wastes.

INDUSTRY	WASTE	METHANE YIELD (L CH_4 $kgSV^{-1}$)	AVAILABILITY (%)		REFERENCES
			MIN	MAX	
Sauceries	Process waste	216	10	25	[27]
	Grease trap sludge	278	50	80	[28]
Slaughterhouses	Ruminal content, manure, other solids	540	50	80	our studies
Poultry	Slaughter waste	550	10	25	[29]
	Grease trap sludge	278	50	80	[28]
Fish	Fish waste	390	10	25	[30]
	Grease trap sludge	278	50	80	[28]
Oil	Blanking earth	400	50	90	[31]
	Biological sludge	340	50	90	[32]
Dairy	Biological sludge	340	50	90	[32]
	Whey	424	5	30	[27]
Wine	Pressing	180	30	50	[33]
	Wine sludge	283	30	50	[33]
	Peduncle	283	30	50	[33]
Brewery and malting	Malting waste	245	70	90	[34]
	Biological sludge	340	70	90	[32]
	Yeast	560	70	90	[35]
Woolscouring	Sedimentation sludge	150	70	90	Estimated
	Recovered grease	150	70	90	Estimated
	Decanter sludge	150	70	90	Estimated

C. *Co-digestion*

The co-digestion benefits have been largely reported in the literature. When using a single residue, some problems could be present [36]. For instance, lipids have important methane potential but require a long time for biodegradation; proteins and carbohydrates have lower methane potential but higher biodegradation velocities. Moreover, the presence of lipids could inhibit the anaerobic process due to the accumulation of fatty acids, or could produce floatation problems or the coating of microorganisms by the fatty material [37]. In contrast, the presence of carbohydrates could produce a pH decrease in the system and proteins could produce an increase in pH. The co-digestion of a mix of substrates minimizes the problems mentioned above and produces economical and technical improvements [38 – 39]. Usually, the co-digestion produces more biogas than the single substrates [40 – 41].

D. *Type of reactors*

Some systems operate in a mesophilic range (35 – 37 °C), and others operate under thermophilic conditions (55 °C) [42 – 43]. Some systems are operated in batch mode, and others are operated in continuous mode. The mixing systems depend on the reactor configuration. Finally, some systems operate with low solid content (5-10%, “wet” digestion), and others operate with high solid concentration (approximately 20%, “dry” digestion) [44 – 45].

Additionally, pretreatment systems as mechanical, chemical, enzymatic or ultrasounds methods can be used to improve the organic matter removal efficiency [46]. Alternatively, some systems are implemented with a solid waste reactor where the hydrolytic phase is performed, followed by a conventional anaerobic reactor to treat the hydrolyzed organic matter in the liquid phase [47]. In some cases, percolating systems are used; the percolated recirculation improves contact and homogenization. A single reactor or several reactors working in sequential mode could be used. In table 5, adapted from Nizami and Murphy (2010) [48], the advantages and disadvantages of the different systems are presented.

IV. ENERGETIC POTENTIAL OF ANAEROBIC DIGESTION

The potential of methanation of a residue is determined by their biodegradability; nevertheless a fraction of the substrate is used for the growth of microorganisms, approximately 10% to 20%. However, the methane obtained from a residue also depends on other factors: type of reactor, temperature, HRT in continuous reactors, reaction time in batch reactors, degree of mixing, microorganisms developed, etc.

To estimate an upper bound of the methane production, the maximum theoretical energy potential can be calculated from the specific methane yield of a residue and the amount of waste generated. However, it must be considered that only a fraction of the produced wastes is collected; in addition, there are possible alternative uses of the residue. The waste generation mode has a clear impact on the amount of waste collected. Usually, the industrial waste is generated in a concentrated way, whereas other residues such as agricultural wastes are generated in a dispersed mode. From the energetic point of view, the produced biogas can be converted to heat, electrical energy or both. The technical possibilities for energy transformation and distribution must be considered in each situation. Finally, the economic, legal and social considerations must be included in a full approach [32].

Some examples may illustrate the biogas potential in Latin America and outside the region. In Uruguay, the total methane potential is between 52 and 84 million cubic meters per year. This is approximately 1.3-2.1% of the total primary energy of the country. Converting the methane potential into electricity produces 21-34 MW of electrical power, which represents 1.9-3.0% of the mean electrical demand [49].

Chamy and Vivanco (2007) [32] estimated the installable potential to generate electricity of approximately 3.5% of Chile’s capacity at this time.

In Colombia the estimated potential is 6000 million cubic meters of biogas per year. This value is approximately 9% of the natural gas supply of this country.

Ribeiro and Silva (2009) [50] indicate that from anaerobic digestion of vinasse, sewage, excreta and landfills, between 1.16-1.24% of the electrical energy of Brazil could be generated.

The former values are similar to those reported for other countries. Gómez et al. (2010) [51] indicated that from anaerobic digestion of the organic fraction of municipal solid waste, sewage sludge and excreta, 2.82% of the electrical generation and 2.0% of the primary energy consumed in Spain could be produced.

According to Poeschl et al. (2101) [52], in Germany in the year 2008, the electricity generation from biogas was 1.6% of the demand and the potential was six times higher.

The projections for the European Union in 2020 are to achieve between 2 and 3% of the primary energy from wastes (1/5 animal waste, 1/5 other wastes, and 3/5 energy crops).

Daniel-Gromke et al. (2011) [53] indicated that between 2.8 and 4.8% of the primary energy could be obtained from biogas in Turkey.

According to NREL (2013) [54], the biogas potential for the USA (including sanitary landfills, wastewaters, animal wastes and other organic wastes) is approximately 420,000 million cubic meters per year, which is equivalent to 5% of the current consumption of gas in the electrical sector or 56% of the consumption of natural gas in transportation. Murray et al. (2014) [55] estimated that biogas generation could account for between 3 and 5% of the gas market in USA.

In the results presented for Latin America, the possibility of the use of energy crops to produce biogas was not considered. In several European countries, particularly Germany, energy crops are co-digested with animal wastes. Depending on the agronomic yield of crops, which is highly variable, the amount of biogas will also be highly variable. Considering a conservative value of 3 tons of dry matter per hectare per year (Smyth et al. (2009) [56] considered four times this value, 12 tDM ha^{-1} $year^{-1}$), 90% of VS content, and a conservative mean value of 250 m^3CH_4 tVS^{-1} (Smyth et al., 2009 [56], used 300 m^3CH_4 tVS^{-1}), 675 m^3CH_4 will be obtained per hectare and per year. Considering the energetic requirements for agronomic operation (12% of the total), pretreatment and mixing (5%), energetic requirement of the digester (15%) and digestate transportation (3%) (from Smyth et al., 2009 [56]), the net energy is 65%, equivalent to 15.3 GJ.

V. DIGESTATE AS SOIL AMENDMENT

The valorization of waste through anaerobic digestion is accomplished by methane production but also by the use of the digestate of solid wastes digestion as nutrients supplier and soil conditioner. Digestates can be considered to be organic amendments or organic fertilizers when properly processed and managed [57]. The expected effects on crops and the soil are promissory [58]. However, further work is required to improve the full-scale experience and to develop a more integrated and energy-efficient scheme of waste management including dewatering, transportation and spreading [59].

VI. CONCLUSION

The application of anaerobic technology presents an interesting potential in Latin-American countries. Considering the characteristics of the productive matrix, anaerobic digestion is a clear choice for the treatment of liquid and solid waste with significant organic content. From the energy point of view, not only do anaerobic treatments require a little amount of energy to operate, but by generating biogas, they become an attractive option for energy recovery from organic matter. Two objectives are successfully met, reducing the environmental impact and achieving renewable energy generation. Additionally, solid waste digestates can be used as soil amendment and improve the agricultural production from an eco-friendly perspective.

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