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Anaerobic digestion of agro-industrial waste: Anaerobic lagoons in Latin America

Digestión anaeróbica de residuos agroindustriales: Lagunas anaerobias en América Latina

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Abstract
In developed countries, the valorization of agro-industrial wastes (AW) using waste-to-energy strategies through anaerobic digestion (AD) is a reality. In Latin America (LATAM), there are different problems in the management of AW from intensive livestock farming. This study aims to provide a pseudo-radiography of AD management systems focusing on covered anaerobic lagoons (CALs) in Latin America. Quantitative and qualitative data from 1,003 scientific papers were synthesized and analyzed to form a database using data science, which allowed evaluation of the congruence of the scientific research with the real problems of LATAM management. Thirty-eight types of inhibition phenomena with 5,264 mentions were addressed in the database. Nitrogen-related AD inhibition phenomena represented 21% of the incidences in this study, besides being the most significant phenomenon in covered anaerobic lagoons in LATAM. The results showed that CALs in the region are the principal AW management systems (mainly bovine and swine manure) and that scientific research in this sector does not address the real problems in the sector.
Keywords: Anaerobic lagoons; anaerobic digestion; data science; agro-industrial wastes; inhibition phenomena.

Resumen
En los países desarrollados, la valorización de los residuos agroindustriales (AW) mediante estrategias de conversión de residuos en energía a través de la digestión anaeróbica (AD) es una realidad. En América Latina (LATAM), existen diferentes problemas en la gestión de los AW provenientes de la ganadería intensiva. Este estudio pretende ofrecer una pseudo-radiografía de los sistemas de gestión de la AD centrándose en las lagunas anaerobias cubiertas (CALs) en América Latina. Los datos cuantitativos y cualitativos de 1,003 artículos científicos fueron sintetizados y analizados para formar una base de datos empleando ciencia de datos, lo que permitió evaluar la congruencia de la investigación científica con los problemas reales de gestión de LATAM. En la base de datos se abordaron 38 tipos de fenómenos de inhibición con 5,264 menciones. Los fenómenos de inhibición de AD relacionados con el nitrógeno representaron el 21% de las incidencias en este estudio, además de ser el fenómeno más significativo en las CAL de LATAM. Los resultados mostraron que las CALs de la región son los principales sistemas de gestión de los AW (principalmente estiércol bovino y porcino) y que la investigación científica en este sector no aborda los problemas reales del mismo.
Palabras clave: Lagunas anaerobias, digestión anaerobia, ciencia de los datos, residuos agroindustriales, fenómenos de inhibición.

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1 Introduction

Human development inevitably generates wastes, classified into three large groups based on their characteristics and origin: municipal solid waste (MSW), hazardous waste, and special waste (SW). The SW is generated mainly in industrial-scale processes does not have the characteristics to be considered MSW or any of the conditions of the CRETIB code (SEMARNAT, 2006). Agro-industrial wastes (AW) can be classified as SW; due to their bromatological and physicochemical characteristics, their localized generation, and the economic and environmental problems generated due to inadequate management. The AW account for 60% (FAO, 2021) of the 11.2 Gt y^{-1} of solid waste generated globally (UN, 2021). The principal generating sources are intensive crop production (cereals, wheat, rice, corn, soybeans, and sugar cane) (FAO, 2014), which generate 3.3 Gt y^{-1} (Gopinath *et al*., 2016); and intensive livestock farming, producing 3.1 Gt y^{-1} of cattle, pigs, poultry and sheep manure (Berendes *et al*., 2018). These activities have a high presence in the United States (US), India, the European Union, and China with 0.47, 0.46, 0.39, and 0.35 Gt y^{-1} of AW, respectively (Eurostat, 2018).

The AW has a variable composition depending on its origin and nature. On a dry basis, they usually have proportions of lignocellulosic components of 43-50%, carbohydrates 32-76%, lipids 3-30%, proteins 2-30%, and 2-10% of ashes (Anwar *et al*., 2014; Gopinath *et al*., 2016; Mejías-Brizuela *et al*., 2016; Ravindran *et al*., 2018; Serrano, 2015). It has been demonstrated that an adequate balance in these proportions is essential for their energetic use (Miramontes-Martínez *et al*., 2021). These residues can be valorized through thermal and biological waste-to-energy (WtE) systems (Yaashikaa *et al*., 2022), in fertilizer production processes (Torrisi *et al*., 2021), and currently through high-tech strategies such as biorefinery processes, which can generate specific high value-added products and biofuels.

Thermal WtE processes from agro-industrial wastes have technical limitations. The moisture content of AW is usually high as 15% (Sadh *et al*., 2018), with average heat values of 1670 kcal kg^{-1} (Awulu *et al*., 2018), compared to 5477 kcal kg^{-1} of dry leaves or branches (Gravalos *et al*., 2016), making AW unsuitable for thermal processes such as incineration, gasification or pyrolysis (Chen *et al*., 2020). E.g., if AW were added to an incineration process from solid waste, the costs would increase 30% (Cassady, 1935), and the greenhouse gas emissions rise additionally 0.5 tCO_2 eq t^{-1} (Johnke, 1998), having damage to public health and handling problems derived from of the ashes (Huiying, 2021).

Anaerobic digestion waste-to-energy (WtE-AD) processes are suitable for treating AW (Monroy-Oropeza *et al*., 2020) In developed countries such as Italy, Germany, the United Kingdom, France, and The United States, energy from these technologies accounts for considerable contributions of their national electricity consumption matrix: 7.9 (Benato & Macor, 2019), 7 (FMFA, 2019), 5.5 (Raugei *et al*., 2020) 4.5 (IEA, 2018) and 4%, respectively; corresponding to the management of 81 (Benato & Macor, 2019), 90 (Achinas *et al*., 2017), 80 (EA, 2001), 73 (Business France, 2017), and 53% of the total AW generated (mainly from livestock and agriculture). These processes are characterized by operating in a co-digestion regime through AW and energy crops, reaching high yields of 400 to 700 L CH_4 kg VS^{-1}.

Different strategies have driven the development of WtE-AD technologies in advanced nations. Germany currently has more than 11,000 WtE-AD plants, 85% of which operate with AW (EBA, 2020), and up to 14% of the agricultural areas are destined to produce energy crops subjected to AD bioenergy purposes (FMFA, 2019). Italy manages its AW by WtE-AD systems (even of 60%), using in a dominant way sophisticated wet and dry anaerobic digesters (Francini *et al*., 2020), multistage digesters, and fluidized bed digesters (Abendroth *et al*., 2015). Of all WtE-AD processes from AW in the United States, 50% operate with plug-flow anaerobic digesters, 31% with continuous stirred reactor (CSTR), and 19% use covered lagoons, most with sophisticated process monitoring and control systems (EPA, 2011). However, that country is developing and installing other AD technologies such as dry digesters, biofilm, and fluidized beds (EPA, 2021).

Many factors contribute to the competitiveness and success of WtE-AD processes in developed countries. Government policies and regulations on AW management that restrict the use of final disposal sites (FDS) and government economic incentives for the energy production from these wastes promote emerging markets based on AW energy recovery technologies. Nevertheless, a common denominator in countries with active participation in the valorization of AW from WtE-AD processes is technology transfer

(Hussain *et al*., 2020). The development of patents is an indicator of effective transfer technology. Germany has generated 7% of worldwide patents concerning WtE-AD from AW, while 5, 3, 2, and 1% of global patents correspond to Italy, France, the United Kingdom, and the United States, respectively (OECD, 2021).

By contrast, WtE-AD processes from AW in developing regions such as Southwest Asia and Latin America (LATAM) are scarce. Less than 1% of the energy matrix of the countries in these regions comes from WtE-AD processes (CFR, 2021). In LATAM countries, the leading management strategies for AW are their application on cropland (70% of AW), the use of final disposition sites for food and lose waste generated in wholesale and processing is 26% (20% and 6%, respectively) (FAO, 2015), and the use of anaerobic lagoons to treat livestock manure (FAO, 2013). The WtE-AD processes from AW in LATAM are incorporated in only 15% of the anaerobic digesters installed (García & Masera, 2016). In this region, these technologies are used as waste management strategies instead of valorization alternatives for energy production purposes.

The WtE-AD processes from AW face many challenges that hinder their economic and energetic competitiveness. In LATAM, the government regulations that restrict the disposal of AW in FDS or agricultural soils are incipient. They are not structured to promote emerging markets for the recovery of waste, such as the case of Germany, where the management of food waste and bovine manure may cost up to 34 USD t^{-1} of waste when the generators use WtE-AD processes for their management/recovery. Another aspect is the government incentives. In Mexico, there are no subsidies for clean energy production through WtE-AD systems, and the support is focused on the installation and start-up of the processes (commonly anaerobic lagoons) (Gutierrez, 2018). Generally, these processes do not have adequate monitoring or good operating practices, which causes low efficiency in CH_4 production and many cases, abandonment of the sites (Miramontes-Martínez *et al*., 2020). In developed countries, Germany subsidized between 0.176-0.311 USD kWh^{-1} of electricity produced in WtE-AD units with a production capacity from 75-2,000 kW (IEEP, 2022). In Italy, the subsidies account for 0.184-0.310 USD kWh^{-1} for units between 300-600 kW (Garcia *et al*., 2019).

In LATAM, most AW management processes are not precisely WtE-AD since only 15% have an electric generator (approximately 36% of the total capital cost is associated with this equipment). 65% of the digesters installed for AW management are covered anaerobic lagoons (over 4,000 according to own results), of which 84% operate under the mono-digestion regime of livestock manure, with scarce temperature and agitation controls, leading to problems of methane inhibition, generally with yields ranging from 0.01-0.02 m^3 CH_4 m^{-3} dig d^{-1} (Rivas-Garcia *et al*., 2015).

The technology transfer towards AW management from anaerobic lagoons is not efficient in LATAM. According to our patentometric study, less than seven patents have been generated per year since 2015 on these topics. Scientific research prefers to implement different management systems that anaerobic lagoons, missed the chance to use the infrastructure available in the region. Through a detailed bibliographic review (using as search criteria the keywords "agro-industrial waste; agroindustrial (some documents use this word) waste; anaerobic digestion; anaerobic lagoon", geographic delimitation of the LATAM region, a period between 1980-2021, excluded review articles, and considering scientific paper from journals indexed to the Journal Citation Reports) more than 1,000 papers and reports from few organizations were founded. The results showed that scientific publications in LATAM report experimental assays with operating conditions different from anaerobic lagoons. Of the total of documents, 684 correspond to laboratory-scale investigations that 94% implement temperature control; 78% include agitation schemes; 54% contemplate mechanical preparation/pretreatment of the substrates, 96% use biodigesters smaller than 10 L, but none of these implements anaerobic digestion reactor lagoon type in their experimental design. There is no in-depth analysis of the current state of AW management systems through AD processes in LATAM (anaerobic lagoons), which allows knowing the main problems, challenges, and opportunities these systems face.

This study aims to conduct a pseudo-radiography of AW management systems from anaerobic lagoons in LATAM, considering geographical location, conditions and operating performance, types of AW managed, and the main inhibition problems in methane production. A data metanalysis methodological scheme was used to systematize and analyze the information from the scientific literature, integrating data science tools, information search computer resources, and statistical tests.

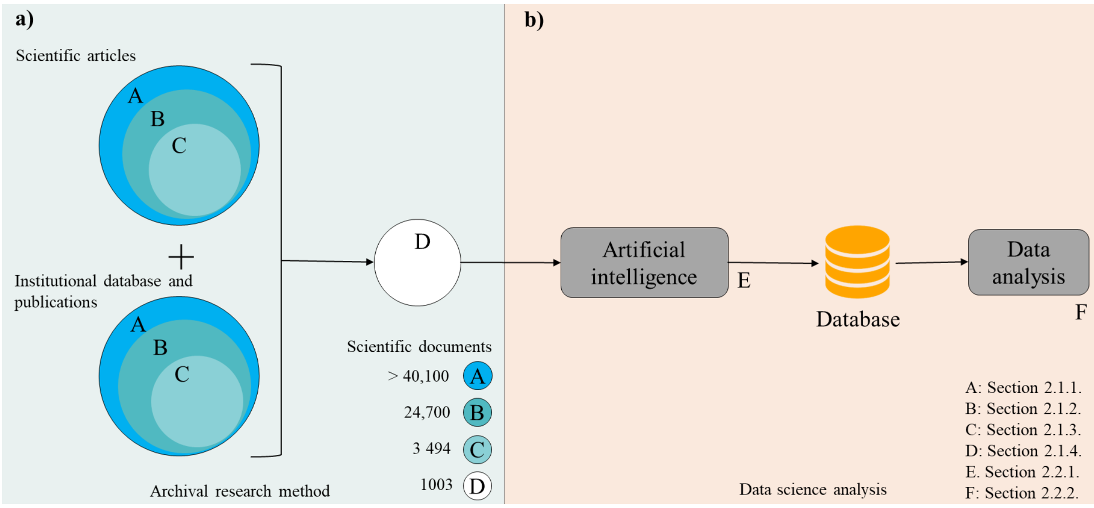


Figure 1. a) The sampling methodology (Archival Research Method). b) Data science analysis.

This work provides knowledge that allows discerning the congruence of scientific research in Latin America with the real problems of the AW management sector with AD processes.

2 Methodology

The methodology was divided into two stages. The first consists of filtering scientific-technological documentation that partially or exclusively studies the topic “anaerobic lagoons in Latin America”, using the archival research method (Section 2.1). The second stage consists of extracting, treating, and structuring the data, statistical evaluation, analysis, and interpretation of the information, using data science tools (Section 2.2). Figure 1 represents the methodological structure, explained in detail in the following sections.

2.1 The Archival research method

The archival research method (ARM) is a strategy to collect, organize, and purge information from published techno-scientific documents around a particular topic (Mentzer, 2003). Sections 2.1.1-2.1.6 detail the ARM to filter efficiently the techno-scientific documents that address the topic “anaerobic digestion of agro-industrial wastes in anaerobic lagoons located in LATAM”.

2.1.1 Definition of sources of information

Two sources of information were considered from different repositories:

1. Scientific articles, hosted in the scientific databases. Elsevier, Wiley, American Chemical Society, Springer, Taylor and Francis, Sage, and Mexican Journal of Chemical Engineering (RMIQ by its acronym in Spanish).

2. Institutional database and publications.

Global organizations: the International Energy Agency (IEA), International Development Bank (IBD), United Nations Industrial Development Organization (UNIDO), Food and Agriculture Organization of the United Nations (FAO), Global Environmental Facility (GEF).

LATAM organizations: Latin American Energy Organization (OLADE by its acronym in Spanish), Network of Biodigesters in Latin American, and the Caribean (RedBioLAC for its acronym in Spanish).

LATAM countries: Mexican Bioenergy Network (REMBIO for its acronym in Spanish), Science Institute of Biogas (CI Biogas for its acronym in Portuguese), and Bi-national ITAIPU organization.

2.1.2 Sampling

A time frame of 1980 to 2021 was defined for the information collection. Some critical publications on this subject were published in the ’80s in LATAM, initially evidencing the situation of the anaerobic lagoons in LATAM. Different Boolean operators were used to request the information, using different keywords according to the following query configuration: "anaerobic digestion" + "agro-industrial waste" OR "agroindustrial waste" + "anaerobic lagoon" OR "anaerobic pond" + region/country + "biogas" OR "methane" OR "biomethane". The results were obtained in Spanish, English, and Portuguese, and the review articles were excluded. The first sampling generated more than 24,700 results.

2.1.3 Regional filtering

Of the 24,700 documents obtained, not all focused their study on Latin America, but some from other regions mentioned some Latin American context in their discussions. Only the techno-scientific documents focused on a Latin American were filtered through human scrutiny, reducing the files to 3,494. A free access software specialized in document management was used (Mendeley ®) to avoid duplicate scientific information.

2.1.4 Screening

In their discussions, several scientific articles included topics WtE-AD of AW through anaerobic lagoons, but the studies' focus was different. The objective and conclusions were carefully reviewed to discard not pertinent information, to select only documents that address the central topic. As a result, a total of 1,003 scientific documents were considered -including scientific papers, databases, and institutional reports.

Figure 1a shows the activities to obtain the final sample, including the number of documents in each methodology step (First Stage).

2.2 Data science analysis

Figure 1b shows the methodology structure to extracting and analyzing de information (Second Stage), explained as follows.

2.2.1 Artificial intelligence to data extracting

Scholarcy ® application was used to identify, extract, synthesize, and organize information from the 1,003 documents. This software is powered by artificial intelligence algorithms using associative indexation for data management (Marchet *et al*., 2021). The structured database was composed of five modules that included quantitative and qualitative data from the total number of documents. The modules are: general data, which includes the authors of the documents analyzed, country of origin, journal, publisher, year, citations, and objective; type of substrate, including origin, treatment, and digestion scheme; operational conditions, including temperature, reactor type, hydraulic retention time (HRT), bioreactor volume, technology, organic loading rate, depth, and scale; results, including yields, efficiencies, quantitative data, methane percentage, and conclusions; and climatology, including temperature and precipitation data, from the locations of the anaerobic lagoons are located in LATAM.

2.2.2 Data analysis

The database was barely used to restructure and organize information and documents in previous stages, refining it according to needs. *Data Science* tools were used, making queries among the various modules to extract useful information and analyze the database. Statistical analysis methods were used: non-parametric statistical tests (E.g., using Kruskal-Wallis test to identify statical differences in data with unknown distribution and different elements size), multivariate methods, principal component analysis, clustering, data screening, and correlation analysis, The correlation of operational conditions, yields, and inhibitory phenomena was analyzed using a non-parametric correlation coefficient, with a significance of 0.05. The *Spearman* correlation coefficient was adequate according to the characteristics of the data (non-normal distribution, continuous and discrete data, and exclusion of outliers) (Triola, 2007). The sequential Bonferroni method (with a level of significance of 0.05) was used to correct the p-value for *Spearman*'s correlation coefficient, to counteract the problem of multiple comparisons, and identify the most important correlations. JMP Statistical Discover v.10 software (Wittington House, Marlow, Buckinghamshire) was used for statistical analysis and Microsoft Excel®, to develop the Bonferroni method.

3 Results and discussion

3.1 AW-AD digesters: principal technologies and geographical distribution

Figure 2 allows visualizing the most common reactor configuration in the global AW management, under laboratory and industrial-scale reactors (more

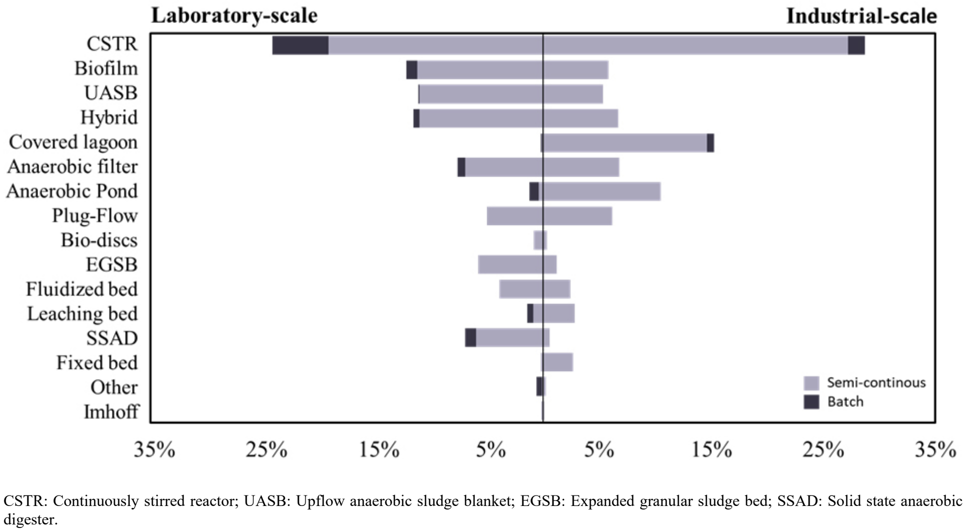


Figure 2. Scale and operating regime of bioreactors.

than 1,000 m^3) operation. A relative balance in scientific documents that address reactors at laboratory and industrial-scale with superior technological sophistication can be observed. This fact can indicate the pertinence of scientific investigation and subsequent technology transfer toward industrial-scale processes. CSTR, biofilm, UASB, hybrid, solid-state, and fluidized bed bioreactors are in developed countries like Japan, Korea, Germany, Switzerland, the United States, and China. These countries allocate 2-4% of their gross domestic product for research and development; on average, more than 1,000 USD per capita y^{-1}. The installation of this type of reactor has an average cost of 0.9 to 2.2 billion USD and operating costs of 25 to 125 USD t^{-1} d^{-1} (Vasco-Correa *et al*., 2018).

Digesters with a less technical degree, such as covered lagoons and anaerobic ponds, are mainly installed in countries with developing economies, such as the LATAM region. The implementation of these technologies is mainly on an industrial-scale with operating volumes of at least 1 000 m^3 and HRT around 130 d, which carries difficulties in studying this technology at the laboratory-scale. The installation of these digesters has an average cost of 55 USD m^{-3} (Wittmann & Liao, 2016), 80% lower than digesters type CSTR, and low O&M costs, 74% lower compared to technologies involving temperature control and agitation (Beddoes *et al*., 2007). Anaerobic lagoons are widely implemented in countries that spend less than 1% of their gross domestic product on research and development, less than 240 USD per capita y^{-1} (Wittmann & Liao, 2016).

The information analysis showed that 63% of the reported anaerobic lagoons are located in Latin America. LATAM produces approximately 15% of the agro-industrial waste produced globally; this waste is susceptible to being managed through anaerobic systems. Anaerobic lagoons operate in mono-digestion schemes 90% of the time, treating mainly agricultural waste since, in this region, there is a lack of regulations and bylaws for the transport of waste to centralized treatment stations that can use more than one substrate. Therefore, most anaerobic lagoons are installed near generation sources that produce only a specific type of waste.

Figure 3 shows the anaerobic digesters distribution in LATAM whit some of their main features. It is possible to recognize how some countries are opting for more sophisticated technologies than anaerobic lagoons, which may be due to government policies or the conditions of the different agro-industrial waste production sites; anaerobic lagoons lack control systems in the region, making them susceptible to climatic conditions. In Argentina and Chile, with annual average temperatures of 8 °C, this technology could present difficulties by operating in a psychrophilic range that is not optimal for the anaerobic process. In Mexico and Brazil, with average temperatures of over 20 °C, the anaerobic lagoons often appear as livestock manure management.

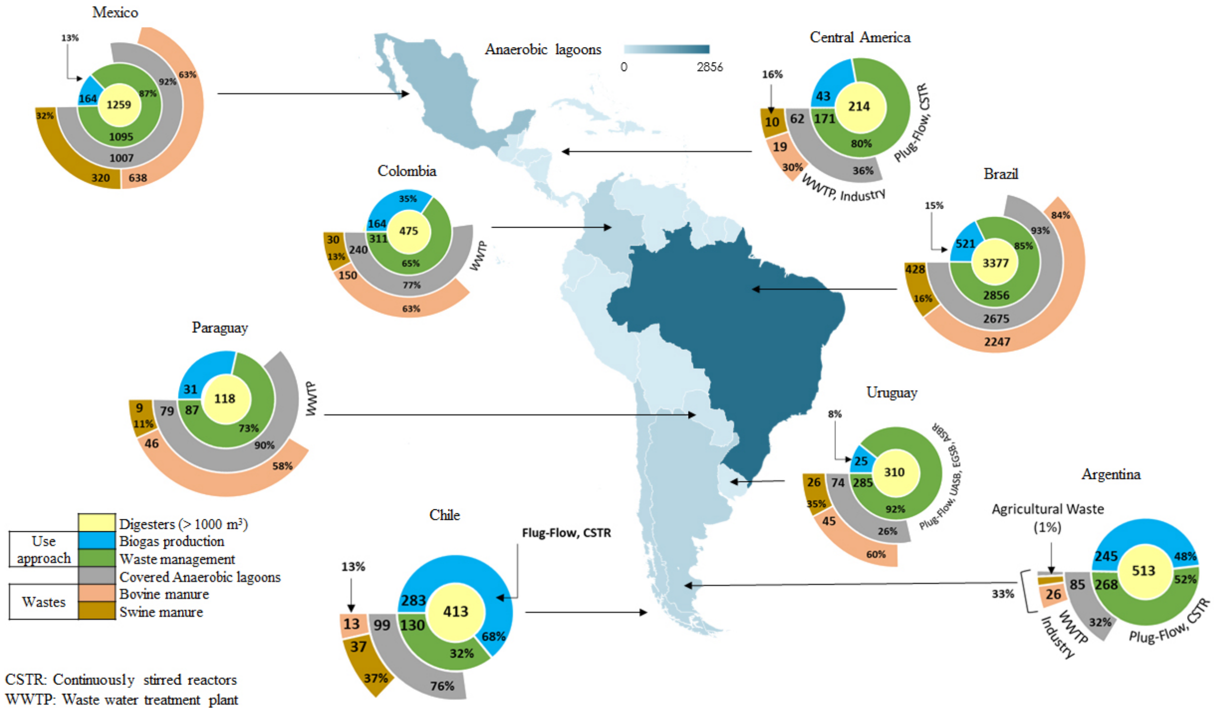


Figure 3. Distribution of biodigesters in Latin America.

Almost all anaerobic lagoons in LATAM (92%) lack temperature and agitation control systems. The influents are treated to comply with environmental regulations and dispose of effluents in the environment without being a risk to health or ecosystems. The installation of covered lagoons and anaerobic ponds was boosted by the Kyoto protocol agreements, which, through the clean development mechanisms and the appearance of carbon credits, encouraged the implementation of this type of technology in Latin America, mainly in Mexico and Brazil, where about 19% of them involved technology transfer (Alemán-Nava *et al*., 2014; Dechezleprêtre *et al*., 2008).

3.2 Anaerobic lagoons in Latin America: general features and operational conditions

Table 1 shows the anaerobic digesters in LATAM, their purpose, and the substrate managed. In LATAM countries, the anaerobic lagoons are mostly installed on farms with more than 1,000 head of cattle. Brazil has practically half of the biodigesters installed, 85% of them are used exclusively for manure treatment, and 93% are lagoons type, susceptible to implementing biogas valorization systems. Most of these processes operate through dairy (84%) and pig manure (16%) management. Brazil is the world's leading cattle producer, with 214 million head, producing 9.5 Mt y^{-1} of meat, and the world's third-largest pig producer with 4.2 Mt y^{-1} of meat (OWD, 2019). 80% percent of intensive livestock farms have lagoon-type waste management systems. Most of these sites are in the south; this country has more than seven million livestock production units, with 34 head of cattle per unit (only 15% of the farms have more than 300 head of cattle). Mexico has approximately 20% of the digesters (preponderantly ACL); 87% focused on waste treatment, where two-thirds use bovine manure as substrate, and the rest operate mainly with pig manure. Mexico is the eighth cattle producer with 35 million heads and the ninth pork producer with 18 million heads (OWD, 2019). Most anaerobic lagoons in Mexico are in intensive farming, primarily in the northwest (Laguna dairy basin) and central zones (Bajío and Jalisco dairy basins), with an average of 26 heads of cattle (9% of the farms have more than 300 cattle units).

Table 1. Anaerobic digesters in LATAM and substrates treated.

Country	Digesters	Digester specific purpose		Covered Anaerobic Lagoons	Manures treated	
		Biogas production	Waste management		Bovine	Swine
Mexico	1259	164	1095	1007	680	341
Brazil	3377	521	2856	2675	2394	456
Argentina	513	245	268	85	28	13
Central America	214	43	171	62	20	11
Chile	413	283	130	99	39	14
Colombia	475	164	311	240	160	32
Paraguay	118	87	31	79	49	10
Uruguay	310	25	285	74	48	28

Table 2. Operational conditions of anaerobic lagoons.

Country	CALs	Temperature (°C)	Digester (m^3)	% CH_4	Biogas Yield (m^3 m^{-3} Dig d^{-1})	OLR (kgCOD m^3 d^{-1})	HRT (d)	With monitoring systems	With control systems	Use HDPE
Mexico	1007	21	5700 ± 1000	70 ± 6	0.05 ± 0.04	0.15 ± 0.05	134 ± 30	15%	7%	85%
Brazil	2675	25	5850 ± 1200	75 ± 7	0.09 ± 0.06	0.18 ± 0.04	121 ± 28	27%	22%	88%
Argentina	85	14.8	4250 ± 950	67 ± 5	0.03 ± 0.01	0.09 ± 0.03	132 ± 16	11%	6%	99%
Central America	62	25.1	3250 ± 810	64 ± 8	0.03 ± 0.03	0.07 ± 0.03	130 ± 25	6%	2%	91%
Chile	99	8.5	3810 ± 1250	65 ± 5	0.02 ± 0.02	0.06 ± 0.05	164 ± 34	9%	7%	70%
Colombia	240	24.5	3895 ± 950	72 ± 7	0.03 ± 0.02	0.12 ± 0.05	101 ± 22	9%	6%	69%
Paraguay	79	23.6	4800 ± 1200	77 ± 6	0.04 ± 0.03	0.11 ± 0.04	137 ± 26	8%	6%	80%
Uruguay	74	17.6	6100 ± 1100	68 ± 7	0.04 ± 0.02	0.12 ± 0.03	120 ± 18	10%	11%	90%
LATAM	**4321**	**20.0 ± 6**	**4700 ± 1050**	**70 ± 6**	**0.04 ± 0.03**	**0.11 ± 0.04**	**130 ± 25**	**12%**	**8%**	**84%**

LATAM: Latin American values average; OLR: Organic loading rate; HRT: Hydraulic retention time, HDPE: high-density polyethylene.

Other Latin American countries, such as Argentina and Chile, are opting to implement other types of strategies for waste management since their production of waste from the agricultural sector is significantly lower than in other Latin American countries, such as Mexico, Brazil, and Uruguay. Argentina and Chile use 52% and 32%, respectively, of their digesters for agro-industrial waste treatment; they have 65 to 75 heads of cattle per livestock production unit, higher than most Latin American countries, but with fewer production units (0.8 and 0. 075 million production units, for Argentina and Chile, respectively). The rest of the biodigesters are used exclusively for energy production, using sophisticated plug-flow digesters and bioreactors with agitation and temperature control. Anaerobic lagoons in these countries are frequently used for wastewater treatment or industrial waste. In the Andean region, the average temperatures range from 8 to 14 °C during the year, so the installation of waste management systems without temperature control is limited, in part, by the environmental conditions. Information from other countries in the region is presented in table one.

Table 2 shows the operational conditions of the CAL present in the main LATAM countries. Mexico and Brazil have the highest number of these systems and have annual temperatures above of LATAM average. There seems to be a direct relationship between whether conditions (specifically between temperature) and the number of installed CAL, fostering or justifying the absence of temperature control in these countries. Countries with low annual temperatures can opt for other technologies like Argentina, Chile, and Uruguay, where the 83%, 76% y 76% of their digesters are plug-flow and CSTR.

Anaerobic lagoons have the lowest methane productivity as a manure management strategy; concerning these, completely-mixed digesters with temperature control can increase their productivity up to 11 times (Cantrell *et al*., 2008; Rivas-Garcia *et al*., 2015). Implementing these systems on dairy farms increases the total costs (digester + generator + O&M) by about 485% compared to lagoon-based systems (Beddoes *et al*., 2007); however, in the short and medium-term, they bring considerable economic and environmental benefits, which can help promote alternative markets for the valorization of manure in dairy and pig production in Latin America.

According to this study, the productivity of anaerobic lagoons in Latin America is on average 0.04 m^3 biogas m^{-3} digester d^{-1}. In general, 812 348 m^3 d^{-1} of biogas are produced daily. Considering the low heating value of biogas and efficiency in electrical co-generation of 0.2 (for co-generation systems in Mexican anaerobic lagoons (Rivas-Garcia *et al*., 2015), there is a potential for electrical generation of 345.8 GWh y^{-1}. Apparently, this amount of energy is high; however, its distribution and use are complicated; Latin America Dairy and pig farms are decentralized, and due to their low biogas productivity, they do not generate the proper technical conditions to use biogas in electric generators, generally.

Manure produced on dairy farms is difficult to degrade in anaerobic digestion due to the high fiber content, 30% of VS (Miramontes-Martínez *et al*., 2021), which leads to HRTs around 130 d in CALs. In these systems, temperature plays a determining role. However, there are other factors to consider. Lack of agitation fosters a low microorganism-substrate interaction, reducing the degradation of organic matter and methane production. In the same way, the scarcity of pretreatments for these wastes means that the lignocellulosic components take longer to hydrolyze, which also causes variation in particle size. These phenomena negatively affect the HRT in the CALs and consequently the operational volume.

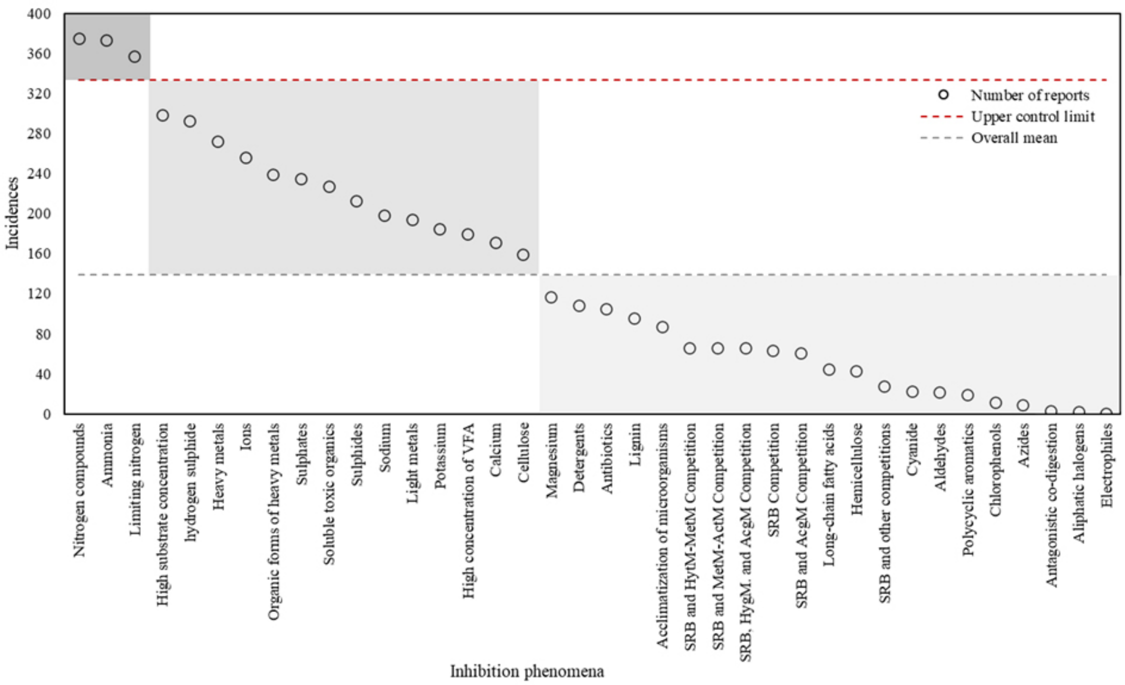
The volume variability of the digester in Table 2 is because, in Mexico and Latin America, the lagoons are installed in farms of different sizes. The biodigester volume corresponds to the amount of manure treated and the design parameters. According to our data, in Mexico, cattle farms producing milk and meat have an average of 26 head of cattle. However, about 6% of the farms have between 300 to 1,000 cattle heads, only 3% have more than 1,000; a similar situation occurs for the other Latin American countries studied. The notable variation in the standard deviation of the other parameters (biogas yield, percentage of methane, organic loading rates, and hydraulic retention time) obey to lagoon design and the influent origin within the cattle farm. Sometimes the influent comes from the milking, breeding rooms, or stockyard washing. These facts cause the physicochemical and bromatological characteristics of the substrates reflected in high standard deviation values in Table 2. Additionally, many lagoons do not operate to produce biogas but rather as solids removal systems.

Another feature in the CALs is high-density polyethylene (HDPE) as cover and waterproofing coating, 84% of the lagoons using it due to its impermeability, flexibility, applicability, handling, and low maintenance costs. The advantage of using HDPE is the adaptability to different terrain conditions and the low costs of acquisition and installation, which range between 1.5 to 2.5 USD m^2 for the most common thickness of these systems (1.20 mm).

3.3 Inhibition phenomena of AW-AD at covered anaerobic lagoons in Latin America

The recurrence of incidences of AW-AD inhibition phenomena in CALs in the database was analyzed; the *Kruskal-Wallis* test showed a p-value of 0.001. Figure 4 shows the occurrences (incidences) that each scientific document presents (5,264 incidences in 1,003 scientific papers, Figure 1a) of the different inhibition phenomena. Values above the upper limit, calculated according to the range rule by doubling the standard deviation of the number of occurrences, are considered statistically significant (Triola, 2007). The three inhibition phenomena reported above the upper control limit correspond to nitrogen-related phenomena, with 7.1, 7.1, and 6.8% of the incidences, respectively, highlighting them as the leading inhibitory problems in the CALs. Inhibition by high N-(NH_3 + NH_4^+) concentrations is historically one of the most studied phenomena in the scientific literature. According to our study, in AD of AW, 899 incidences in database address this problem in the period between 1980 and 2021. However, the inhibition phenomena related to high concentrations of nitrogenous species in solution continue to be the most common in Latin American CALs.

In Figure 4, two clusters in the inhibition phenomena can be identified in addition to nitrogenous compounds. In the second, micronutrients (sodium, potassium, and calcium), heavy metals, sulfur compounds, and high concentrations of substrates and intermediate metabolites are observed. Considering the years of publication of the documents that deal with these problems, it is found that these topics have been published in 2009 ± 6, showing that they are topics not so recently studied in covered anaerobic lagoons in LATAM. The third group is below the overall mean, this type of phenomenon is addressed in less proportion in the literature, but its temporality in research is recent, the average year of publication is 2016 ± 4.7. Within this group, research on competitive inhibition in microorganisms is distinguished and the presence of emerging contaminants. These topics correspond more to avant-garde and frontier research since, on average, they are published in journals that together have an impact factor of 6.125 ± 2.16. In addition, the study of these issues requires sophisticated analysis equipment with high maintenance costs.



VFA: Volatile fatty acids; SRB: Sulphate reducers bacteria; HytM: Hydrogenotrophic microorganisms; MetM: Methanogenic microorganisms; ActM: acetoclastic bacteria; HygM: Hydrogeophytes microorganisms; AcgM: Acidogenic microorganisms.

Figure 4. Inhibition phenomena incidences on the database.

Table 3 presents different concentrations of inhibition species according to our database. These inhibition ranges correspond specifically to CALs in Latin America, which, as discussed in detail in Sections 3.1 and 3.2, lack automated control systems and feed practically on effluents from cattle and pig farms.

Evaluating inhibition by competition of microbial groups is complex due to the multiple operational conditions, influent characteristics, and microbial consortia in the different substrates. Being a biological process, the concentration of the different microbial groups and their dynamic behavior are critical in the AW-AD process. Bioassays can be performed by implementing a confrontation technique to evaluate the competition of the different microbial groups in different culture media under similar operational conditions than CALs (Ramos *et al*., 2009). One of the solutions more studied to face the inhibition problems is the addition of co-substrates; however, it sometimes causes antagonism, especially with those substrates that foster the formation of toxic species (such as poultry manure, with up to 3% nitrogen w/w, which favors ammonia formation) or with physicochemical characteristics that affect the biochemical processes, such as high salt contents.

3.3.1 Industry and laboratory-scale inhibition phenomena

Figure 5 shows the 17 inhibitory phenomena with a higher proportion in our database. The bar's length indicates the percentage of investigations showing different inhibition phenomena in the CALs. In turn, each bar indicates the proportion of the existence of these problems: industrial or laboratory-scale. The dotted line represents a pseudo balance, ratios above the line indicate that the inhibition phenomena have a bias to appear in industrial projects, ratios below indicate that the problems are more studied at the laboratory-scale and are few the reports of their incidence in industrial-scale.

In the left of Figure 5, the inhibition phenomena related to nitrogenous species stand out. Nitrogen compounds and ammonia correspond to recurring problems AW-AD processes (De La Cueva *et al*., 2021). Scientific studies at the laboratory-scale related to these problems are numerous in the context of CALs

Table 3. Inhibition levels of inhibition phenomena at anaerobic lagoons in LATAM.

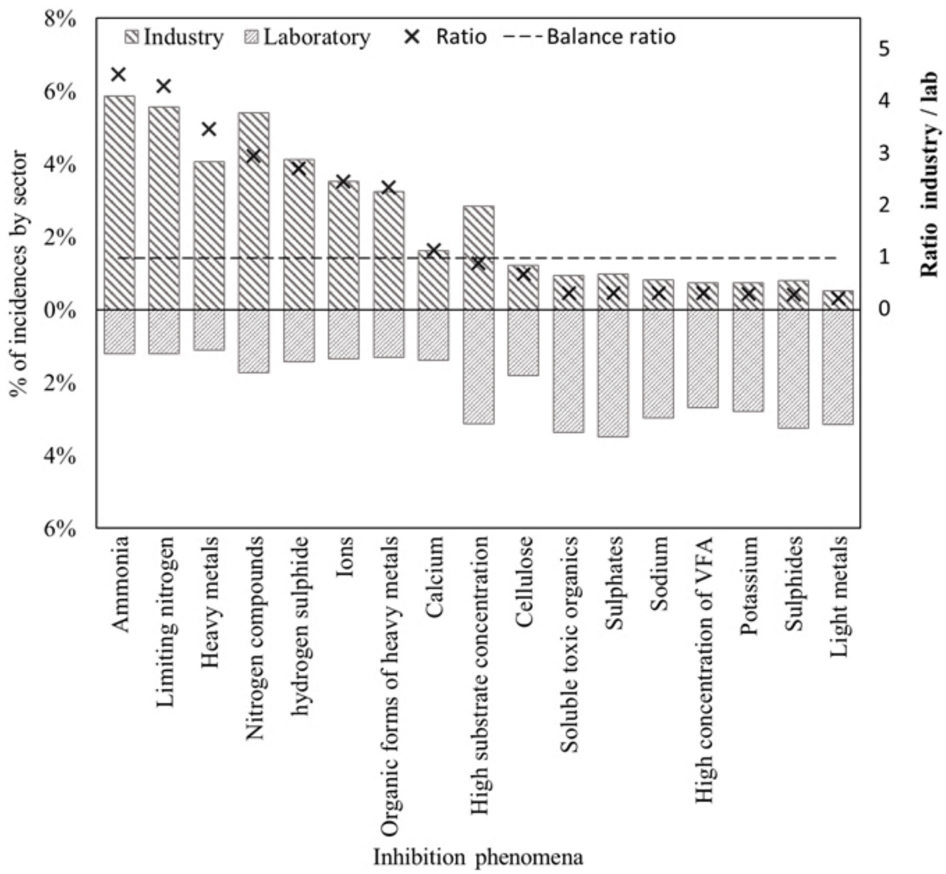
Inhibition phenomena	**Strong inhibitory values**
Ammonia	1500 - 3500 mg L^{-1}
Limiting nitrogen	< 500 mg L^{-1}
High substrate concentration	2.5 - 4.5 kg VS m^{-3} d^{-1}
hydrogen sulphide	200 - 600 mg L^{-1}
Heavy metals	9000 - 1500 mg L^{-1}
Ions	700 - 900 mg L^{-1}
Organic forms of heavy metals	600 - 1000 mg L^{-1}
Sulfates	50 - 150 mg L^{-1}
Sulphides	100 - 200 mg L^{-1}
Sodium	7000 - 9000 mg L^{-1}
Light metals	500 - 8000 mg L^{-1}
Potassium	10000 - 12000 mg L^{-1}
High concentration of VFA	2000 - 4000 mg L^{-1}
Calcium	7000 - 9000 mg L^{-1}
Magnesium	2000 - 4000 mg L^{-1}
Detergents	30 - 50 mg L^{-1}
Antibiotics	15 - 40 mg L^{-1}
Lignin	2 - 150 mg L^{-1}
Long-chain fatty acids	30 - 100 mg L^{-1}
Cyanide	1 - 2 mg L^{-1}
Aldehydes	0.5 - 1 mg L^{-1}
Polycyclic aromatics	25 - 150 mg L^{-1}
Chlorophenols	270 - 550 mg L^{-1}
Azides	> 160 mg L^{-1}
Aliphatic halogens	> 15 mg L^{-1}
Electrophiles	> 0.1 mg L^{-1}

VFA: Volatile fatty acids; TN: Total nitrogen

in Latin America (899 reported incidences), indicating that there has not been an efficient mechanism for transferring knowledge between academia and industry. Figure 5 also shows that problems with the highest incidence in CALs are related to the presence of heavy metals and H_2S. The origin of heavy metals can come from livestock feed due to the application of inorganic fertilizers and treated water for irrigation (Reyes Pinto *et al*., 2020), which represents an area of opportunity for research studies to mitigate this problem.

On the right of Figure 5, there are the problems whose research and study are focused on the laboratory level (ratio < 1). Evaluating and analyzing these inhibition phenomena require sophisticated and expensive analysis equipment due to the requirements of measurements of elements and chemical substances in solution within a complex matrix (anaerobic medium). The phenomena on the right side of Figure 5 do not have much presence on an industrial-scale; this does not mean that these problems do not exist; the CALs in Latin America lack effective sampling systems, specialized labor for their operation, as well as the absence of strategies for measuring operational parameters in situ, which can mask the real problems.

The quantification of volatile fatty acids (VFA), such as acetic acid, usually constitutes 60-70% of the VFA in AW-AD (Rivas-García *et al*., 2020) is scarce on an industrial-scale. The methodology used for their quantification usually requires chromatography equipment, which is sometimes available at a laboratory-scale. The measurement of substrate concentration in CALs is straightforward to analyze; it requires essential laboratory equipment (such as a laboratory oven) and does not represent a considerable monetary outlay for its acquisition. Hence, there is a trade-off in their inhibition reports due to this phenomenon on an industrial and laboratory-scale. This inhibition phenomenon is a recurrent problem in the CALs, probably due to the variability of the influent.



VFA: Volatile fatty acids.

Figure 5. Inhibition phenomena at industry and laboratory scale.

3.3.2 Statistical correlation of operating conditions and inhibition phenomena

Table 4 shows statistically significant correlations between operational conditions, yields, soluble compounds, and substrate concentration according to the Bonferroni sequential method for *Spearman*'s coefficient p-values. Values close to 1 in the *Spearman* coefficients indicate a synergistic relationship between variables, values close to -1 are characteristic of antagonistic relationships.

In Table 4, the concentration of nitrogen species is the factor with the highest incidence. Its high concentration is usually associated with low biogas yields, $\%CH_4$, and inhibition problems in Latin American CALs, mainly those that manage waste from bovine farming. Free ammonia, related to substrate concentration in bovine manure CALs, is associated with inhibition phenomena; high ammonia concentration negatively affects the metabolism of acetoclastic methanogenic microorganisms, which leads to accumulation of acetic acid and eventually acidification of the medium (Angelidaki *et al*., 1993), this is one of the most common problems in DA of substrates with high contents of $N\text{-}NH_3$ and proteins.

A positive correlation can be observed between the high substrate concentration with lagoons treating swine manure. Pig feed usually presents variations in its composition depending on the products available in each region. Sometimes they are fed with fodder, grains, food waste, and fruit and vegetable waste, which usually vary considerably (Paranhos da Costa *et al*., 2012).

Calcium also appears as a factor with a positive impact on biogas productivity and $\%CH_4$. This species in anaerobic media commonly appears in the form of calcium-containing alkali materials, which have buffering effects on pH due to the accumulation of VFA, generating anaerobic environments propitious and stable for methane production and sometimes some help to reduce heavy metals (Yang *et al*., 2021).

Table 4. Statistical correlations of general factors in Latin American anaerobic lagoons.

Factors		***Spearman* coefficients**	**p-value (Adjusted by *Bonferroni* method)**
Calcium	Biogas productivity	0.9966	0.0001
Soluble toxic organics	High substrate concentration	0.9954	0.0002
Nitrogen compounds	Soluble toxic organics	0.9952	0.0004
Calcium	$\%CH_4$	0.9893	0.0004
Ammonia	High substrate concentration	0.9725	0.0004
Ammonia	Bovine manure anaerobic lagoons	0.9587	0.0004
High substrate concentration	Swine manure anaerobic lagoons	0.9543	0.0006
Calcium	Depth	0.8974	0.0008
Heavy metals	Depth (m)	0.8406	0.0009
Calcium	Heavy metals	-0.985	0.0009
Calcium	HRT	-0.932	0.001
Sulphides	HRT	-0.9405	0.0011
Ammonia	$\%CH_4$	-0.9772	0.0012
Nitrogen compounds	Hydrogen sulphide	-0.9934	0.0013

The source of calcium in CALs can come from the intake of $CaCO_3$ in dairy farms, which is an essential nutrient for increasing milk production (Clark *et al.*, 1989).

This work is based on an exhaustive review of 1,003 sources of scientific information on the topic of CALs in Latin America (Figure 1), which were analyzed by data science tools. The relationships in Table 4 correspond to statistical evaluations with greater significance in the *Spearman* coefficient. The greater depth of these relationships' origins is considered outside the scope of this investigation.

Conclusions

This study validated the usefulness of new disciplines for information management, such as data science, to analyze a complex situation in a context that lacks information on the topic: anaerobic lagoons in Latin America for agro-industrial waste management.

In Latin America, about 65% of biodigesters are covered anaerobic lagoons (CALs), of which 77% are designed for waste treatment and not as waste-to-energy processes. The infrastructure installed in more than 4,300 CALs is not suitable to produce bioenergy. Most of these systems are decentralized, adjacent to livestock production units, and were installed promoted by the Kyoto Protocol agreements, serving as a promoter of government and private financing, which in Latin America were used for the installation but not for their operation for a long-time. Most of the CALs are installed on cattle farms (79%) implies meat and milk production processes, fundamental activities in countries such as Mexico and Brazil. Both countries are significant meat producers (1st and 8th, respectively) and milk (16th and 5th, respectively). Most of the CALs are installed in individual intensive farms (there are very few that operate in a centralized regime) and have the main objective to satisfy the local environmental regulations for waste and water disposal.

The study of the CALs in Latin America at a laboratory-scale is scary, probably fostered by their high operating volume, high hydraulic retention time, and the low popularity that the CALs have gained over the years as management/valorization strategies of agro-industrial waste.

Inhibition by ammonia is the most representative inhibitory phenomenon evidenced in this study. However, this problem has been widely studied; there are 899 incidences in scientific documents in the study region that discuss topics related to the problem of ammonia in the anaerobic digestion of agro-industrial wastes. This situation can indicate the pertinence of scientific investigation, but there has not been an efficient mechanism for transferring knowledge between academia and the productive sector.

There is research on CALs that addresses issues that are not commonly reported as core problems, such as research on competitive inhibition in microorganisms and the presence of emerging contaminants. These topics correspond more to avant-garde and frontier research since, on average, they are published in journals that together have an impact factor of 6.125 ± 2.16. Studying these issues requires sophisticated analysis equipment that needs knowledgeable users and high maintenance costs, which is complicated to install and maintain in CALs.

Scientific research in Latin America within the framework of anaerobic covered lagoons should take advantage of the available infrastructure, socioeconomic conditions, the workforce in the farms, and the bioenergy potential of agro-industrial should be considered to develop future development research to address the weakness identified in this study. One of the most propitious options is to adapt the mathematical modeling to the operational conditions of the CALs to be able to foresee adverse events since it is a low-cost strategy, validated and congruent with the Latin American context, and that does not require a considerable investment in monitoring and control equipment.

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Nomenclature

ActM	Acetogenic microorganisms
AcgM	Acidogenic microorganisms
CSTR	Continuously stirred tank reactor
EGSB	Expanded granular sludge bed
HDPE	High-density polyethylene
HytM	Hydrogenotrophic microorganisms
HRT	Hydraulic retention time
HygM	Hydrogeophytes microorganisms
MetM	Methanogenic microorganisms
OLR	Organic loading rate
SRB	Sulfate-reducing bacteria
SSAD	Solid-state anaerobic digester
TN	Total nitrogen
USAB	Up-flow anaerobic sludge blanket
VFA	Volatile fatty acids

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