University of São Paulo
“Luiz de Queiroz” College of Agriculture

Dry anaerobic digestion treatment potential for the organic fraction of municipal solid waste in Brazil and Mexico

Rodolfo Daniel Silva Martínez

Thesis presented to obtain the degree of Doctor in Science.
Area: Bioenergy

Piracicaba
2021

Rodolfo Daniel Silva Martínez
Civil Engineer

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **ALESSANDRO SANCHES PEREIRA**

Co-advisor:
Prof. Dr. **ANTONIO SAMPAIO BAPTISTA**

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CONTENTS

RESUMO

Potencial de tratamento da fração orgânica de resíduos sólidos urbanos por digestão anaeróbica seca no Brasil e no México

Há várias tecnologias de digestão anaeróbia (DA) desenvolvidas e implementadas no Brasil e no México para tratar a fração orgânica de resíduos sólidos urbanos (FORSU). No entanto, as mesmas ainda estão longe de contribuir significativamente, não só para tratar os volumes cada vez maiores de resíduos na região, mas também para suprir a demanda energética regional, recuperar nutrientes e cumprir as metas nacionais de emissão de carbono. Este estudo visa determinar a viabilidade de implementação de tecnologias de DA, e mais especificamente de tecnologias de digestão anaeróbia seca, para tratar a FORSU avaliando os benefícios e vantagens técnicas e ambientais que essas tecnologias oferecem; e em segundo lugar, propor as diretrizes da política para implementação e disseminação de tecnologias de DA com base no marco regulatório no Brasil e no México. Para tanto, a pesquisa utiliza métodos mistos de pesquisa. Primeiramente, realiza uma análise ambiental e uso de recursos para comparar dois estudos de caso no Brasil: Um digestor anaeróbio úmido (WAD) em Foz de Iguaçu e um digestor anaeróbio seco (DAD) localizado no Rio de Janeiro. Essa análise inclui a avaliação do fluxo de água, materiais e nutrientes, eficiência energética e mitigação de emissões de gases de efeito estufa (GEE) como as categorias mais relevantes, buscando a tecnologia mais eficiente. A análise deste estudo de caso foi então complementada com uma revisão da literatura e de políticas públicas, e uma série de entrevistas com pesquisadores e especialistas em políticas públicas para identificar as limitações, desafios e oportunidades para aplicar a DA, a partir de uma perspectiva governamental. Os resultados indicam que mesmo quando o sistema WAD oferece diversas vantagens para economizar recursos, geração de bioenergia, e mitigação de emissões de gases de efeito estufa, há uma eficiência significativamente maior no sistema DAD. O sistema DAD (1) utiliza menos água em seus processos; (2) produz quase 2,5 vezes mais biofertilizantes; (3) possui uma significativa eficiência energética, utilizando internamente menos energia do biogás produzido; e (4) também apresenta um potencial de mitigação de GEE mais significativo. Além disso, quanto à análise de políticas e entrevistas, de acordo com os resultados desta pesquisa, alguns dos principais desafios detectados em ambos países são apresentados devido a: (1) uso excessivo de aterros e lixões; (2) falta de sistemas de segregação de resíduos; (3) falta de conhecimento ou interesse em tecnologias de DA; (4) baixa escolaridade e formação social na área; (5) diversos fatores econômicos; (6) falta de estrutura regulatória e infraestrutura para biogás ou biometano; e (7) deficiências de políticas públicas. Assim, este estudo resultou na elaboração de apontamentos e recomendações para políticas que podem servir para enfrentar esses desafios e desenvolver um plano político nacional para implementar projetos de AD em grande escala para tratar a FORSU. Estas são orientadas para preparar e implementar nova legislação e reformas para desenvolver medidas mais específicas e coercivas para superar os desafios e para o tratamento adequado da FORSU com biodigestores. Em última instância, a necessidade crucial de implantação e disseminação de biodigestores com o tratamento adequado da FORSU surge da necessidade de mitigar os impactos ambientais, sociais e de saúde pública causados pelas rotas tradicionais de disposição de resíduos orgânicos em lixões e aterros sanitários. Esta pesquisa prova que a DAD pode contribuir para essa tarefa, oferecendo diversos benefícios tangíveis para a sociedade e o meio ambiente.

Palavras-chave: Digestão anaeróbia, Bioenergia, Biogás, Avaliação ambiental, Fração orgânica de resíduos sólidos urbanos, Política pública, Gestão de resíduos

ABSTRACT

Dry anaerobic digestion treatment potential for the organic fraction of municipal solid waste in Brazil and Mexico

Anaerobic Digestion (AD) technologies have been developed and implemented in Brazil and Mexico to treat the organic fraction of municipal solid waste (OFMSW). However, they are still far away to significantly contribute to treating the ever-increasing waste volumes in the region and supply the regional energy demand, recuperate nutrients, and meet national carbon emission goals. This study aims to determine the feasibility of implementing AD, and more specifically dry anaerobic digestion (DAD) technologies, to treat the OFMSW evaluating the technical and environmental benefits and advantages these technologies offer, and secondly to propose the policy guidelines for implementing and disseminating AD technologies based on the existing regulatory framework in Brazil and Mexico. For this purpose, the research uses mixed methods research (MMR). It firstly performs an environment and resource use analysis to compare two case studies in Brazil: A wet anaerobic digester in Foz de Iguaçu and a dry anaerobic digester localized in Rio de Janeiro. This analysis includes an assessment of the water, material, and nutrients flow, energy efficiency, and mitigation of greenhouse gas emissions (GHG) as the most relevant categories, seeking the most efficient technology. A literature and public policy review and a series of interviews with researchers and public policy specialists to identify the limitations, challenges, and opportunities to apply AD from a governmental perspective complemented the case study analysis. The results indicate that even when the wet anaerobic digestion (WAD) system offers various advantages of water and resource savings, energy generation, and CO_{2eq} emissions savings, there is a notable significant higher efficiency of the DAD system. (1) It utilizes less water throughout its processes; (2) it produces almost 2.5 times more solid digestate or biofertilizer; (3) it has significant energy efficiency, utilizing internally less energy of the biogas produced; and (4) it also presents a more significant GHG mitigation potential. Moreover, as for the policy analysis and interviews, according to this research findings, some of the detected main challenges in both countries are presented due to: (1) landfill and dumpsites overuse; (2) lack of waste segregation systems; (3) lack of knowledge or interest in AD technologies; (4) low education and social training in the field; (5) diverse economic factors; (6) lack of regulatory framework and infrastructure for biogas/biomethane; and (7) public policy deficiencies. Thus, this study resulted in a series of policy guidelines and recommendations that may serve to face these challenges and develop a national political plan to implement large-scale AD projects to treat the OFMSW; these may assist decision makers to prepare and implement new legislation and reforms to build more specific and coercive measures to overcome the challenges and for the adequate treatment of OFMSW with biodigesters. Ultimately, the crucial need to implement and disseminate biodigesters as the proper treatment of the OFMSW arises from the need to mitigate the environmental, social, and public health impacts caused by traditional practices of disposal of organic waste in dumps sites or sanitary landfills. This research proves that DAD can remarkably contribute to this task offering tangible diverse benefits to society and the environment.

Keywords: Anaerobic digestion, Bioenergy, Biogas, Environmental assessment, Organic fraction municipal solid waste, Public policy, Waste management

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ACRONYMS AND ABBREVIATIONS

1G	First-generation biofuels
2G	Second-generation biofuels
ABiogas	Brazilian Biogas Association
AD	Anaerobic digestion
AD1	Anaerobic digester 1 (Foz do Iguaçu)
AD2	Anaerobic digester 2 (Rio de Janeiro)
AHP	Analytical hierarchy process
AMBB	Mexican Association of Biomass and Biogas
ARM	Archival Research Method
BEP	Energy Program for Brazil
BMP	Biochemical methane potential
C/N ratio	Carbon and nitrogen ratio
CDM	Clean development mechanism
CEMIE-BIO	Mexican Centers for Energy Innovation / Gaseous Biofuels Cluster
CERs	Certified Emissions Reductions
CH_4	Methane
CHP	Combined heat and power
CIBiogas	International Center for Renewable Energy – Biogas
CNBiogas	Mexican National Biogas Commission
CO	Carbon monoxide
CO_2	Carbon dioxide
CSTR	Continuous stirred tank reactors
DAD	Dry anaerobic digestion
Ei	Energy consumption
Embrapa	Brazilian Agricultural Research Corporation
Eo	Energy production
ER	Energy ratio
F/M	Food to microorganism ratio
FL	Fresh Leachate
GEF	Global Environment Facility
GHG	Greenhouse gases
GWP	Global warming potential
H_2	Biohydrogen
H_2S	Hydrogen sulfide or Sulfhydric acid
HCF	High calorific fraction
HSW	Household solid waste
IEE/USP	Institute of Energy and Environment/ The University of São Paulo
INDCs	Intended Nationally Determined Contributions
InPU	Inoculum Production Unit
IPU	Itaipu Production Unit
LAC	Latin America and the Caribbean
LCA	Life cycle assessment
LCI	Life cycle inventory

LHV	Low heating value
MCDA	Multicriteria decision analysis
MD	Digested material
MESB	Reactors Solid State Batch Methanization
MFA	Material Flow Analysis
MFC	Microbial fuel cell
MMR	Mixed method research
MSW	Municipal Solid Waste
N_2	Nitrogen
N_2O	Nitrous oxide
NDCs	Nationally determined contributions
NGOs	Non-governmental organizations
NH_3	Ammonia
NO_x	Nitrogen oxides
O_2	Oxygen
OAS	Organization of American States
OFMSW	Organic fraction of municipal solid waste
OM	Organic matter
OWtE	Organic waste-to-energy
PDE 2030	Ten-Year Energy Expansion Plan
pH	Potential of hydrogen
PLANSAB	National Basic Sanitation Plan
PNE 2050	National Energy Plan 2050
PNRS	National Solid Waste Plan
PT	Preliminary treatment
R&D	Research and Development
RedBioLac	Network for Biodigesters in Latin America and the Caribbean
RTU-Caju	Residues Treatment Unit Caju
SADER	Secretariat of Agriculture and Rural Development
SAGARPA	Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food
SJR	SCImago Journal Rank
SO	Specific objectives
TS	Total solids
UASB	Up-flow anaerobic sludge blanket
UDs	Brazil project as demonstration units
UFMG	Federal University of Minas Gerais
UNICAMP	University of Campinas
UNIDO	United Nations Industrial Development Organization
USP	University of São Paulo
UTR	Residues Treatment Unit
VFA	Volatile fatty acids
VS	Volatile Solids
WAD	Wet anaerobic digestion
WtE	Waste-to-energy

UNITS OF MEASUREMENT

GW	Gigawatt
GWh	Gigawatt hour
Kg	Kilograms
KW	Kilowatt
KWh	Kilowatt-hour
Lit	Liters
m^3	Cubic meters
mg	Milligrams
MJ	Mega joules
Mm^3	Thousand cubic meters
Mt	Megatonnes (1,000,000 metric tonnes)
MW	Megawatt
MWh	Megawatt hour
Nm^3	Normal cubic meters
t	tonnes
TW	Terawatt
TWh	Terawatt hour

1 INTRODUCTION

Scientists and government officials have successfully performed several studies and actions worldwide to apply organic waste-to-energy (OWtE) technologies for managing and treating organic residues (e.g., biowaste). In Brazil and Mexico, biotechnologies have already been upgraded and implemented for this purpose. Nevertheless, there is still a long way to significantly suffice their waste treatment and ever-increasing fertilizers needs and energy demands. Hence, the OFMSW and agricultural residues[1] are not sufficiently recognized as valuable resources with significant energy and resource potential, and biotechnologies, such as anaerobic digestion (AD), are still largely unused [1].

The diffusion of AD technologies is necessary for the sustainable management and treatment of organic residues. The increase of municipal waste in these countries is currently an acute problem, translating into significant health and environmental issues (e.g., watershed contamination, pests, diseases transmission, among others). AD technologies can also significantly reduce dependence on fossil fuels and produce bioenergy and considerable amounts of digestate potentially used as fertilizer. In addition, these countries could benefit from AD technologies to reduce greenhouse gases (GHG) emissions, hence, attaining their national goals established by the nationally determined contributions (NDCs) under the Paris Agreement adopted in December 2015 [2].

In Latin America, various AD technology types have been implemented; however, research and development of these technologies have been focused mainly on small-scale projects, fixed dome anaerobic digesters, and cover lagoons. These are typically used to produce biogas for heating and cooking purposes [1] and electricity generation – mostly in Brazil [3]. Nevertheless, these technologies usually do not produce electricity for communal use – except in Brazil, where there are various projects for distributed generation– and biogas is already a source of revenue or used as biofuel for the transportation sector. One of the main reasons is the low investment cost and low maintenance needs these specific technologies demand.

Notwithstanding, the continuing increase of electricity rates and demand, and acute environmental problems due to the high increase of municipal and agricultural wastes in the region, have made local stakeholders (such as farmers, waste managers, researchers, or decision-makers) look for ways to optimize existing waste treatment systems; thus, allowing for biogas and electricity production [4], in larger scales. Hence, stakeholders have lately considered the idea of searching for and implementing affordable second-generation large-scale AD methods. More than a hundred large-scale continuous stirred tank reactors (CSTR), up-flow anaerobic sludge blanket (UASB), and cover lagoons have been successfully implemented in Brazil and Mexico; these technologies mainly treat specific agricultural and liquid residues or wastewaters. More specifically for the treatment of the organic fraction of municipal solid waste (OFMSW) and solid agricultural residues, recently a debate has been raised on whether specialized technologies,

[1] For practical means, this research, as pointed out by (Jones, 1978) [318], defines the term "residue" as the solid by-products that have some positive value or represent no cost for disposal. The materials that represent a disposal cost or not recognized value are defined as "solid wastes". However, in this research these terms might be used in both conditions since some organic materials may fall into both categories depending on the specific site, as the same author states.

such as dry anaerobic digesters (DAD), or also called solid-state anaerobic digestion, can more efficiently assist on meeting regional waste treatment, biofertilizer production, and energy demands.

DAD systems considered an emerging technology for agricultural and urban residues treatment, have been lately studied and implemented throughout the world, mainly in Europe. This research bases on the theory that these technologies could be feasible for waste treatment, water-saving management, and a renewable energy source in the studied countries. These technologies offer considerable advantages over other treatment methods, such as reducing the water footprint in comparison to WAD. In addition, as second-generation bioenergy technologies, they can mainly save significant greenhouse gas emissions and lower environmental burdens. At the same time, they offer the advantage that the provision of waste materials does not require substantial energy input or additional land, in contrast to the agricultural expansion of the first-generation biofuel production [5].

Aside from these advantages, the importance of dry systems also lies in utilizing considerably fewer water quantities during its processes. They use organic residues with high contents of total solids. Hence, these technologies could be implemented in water-stressed zones, where WAD systems are not viable due to their water demands. Furthermore, this condition will depend aside of the water availability, on the humidity contents of the residues. In Brazil, the Northeast region is affected by droughts, increasing due to climate change, and making it a water-stressed zone. This region, with 28% of the total Brazilian population, comprises of the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, and Bahia; and the dry zone also include the north of the state of Minas Gerais (Figure 1). Within its diversity of biomes (i.e., Cerrado, Caatinga, etc.), this region has a large production of agro-industrial products (e.g., cassava, beans, corn, etc.), and at the same time, suffer from water scarcity in several areas [6]. There is also an existing potential to implement DAD systems in regions with high humidity rates, for example considering the disadvantages caused by rain to composting processes [7].

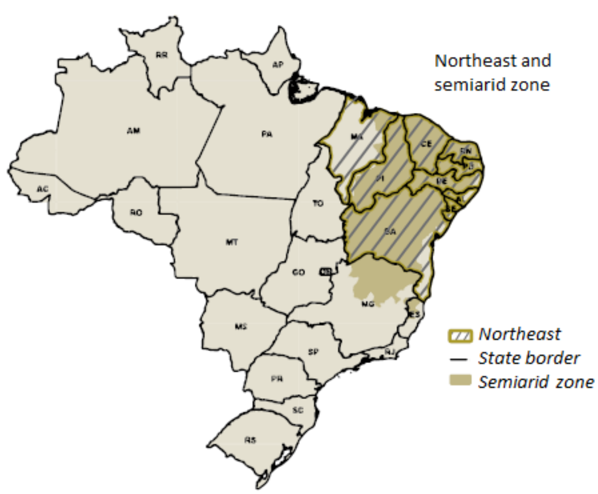

Figure 1. Map of Brazil Northeastern states and semiarid zone. Source: Engle et al. (2016) [6]

In Mexico, water scarcity is currently a significant issue. While most of the country has a certain level of hydric stress, the states of Aguascalientes, Baja California Sur, Chihuahua, Coahuila, Durango, Guanajuato, Mexico City Nuevo León, Sinaloa, Sonora, and Zacatecas are some of the most affected by this issue [8]. Water scarcity results in problems such as infertility and salinization of soils, reduction of the natural recovery capacity of the land, increased flooding in the lower parts of the basins, sedimentation of water bodies, among others. In these dry areas in 2011, 33.6 million people were living, equivalent to 30% of the country´s population [9]. At the same time, these states have large residues generation of crop plantations such as orange, melon, corn, cotton, watermelon, potato, wheat, beans, and diverse types of pumpkins, among others, which farmers and other stakeholders can use as a source of bioenergy, via DAD technologies.

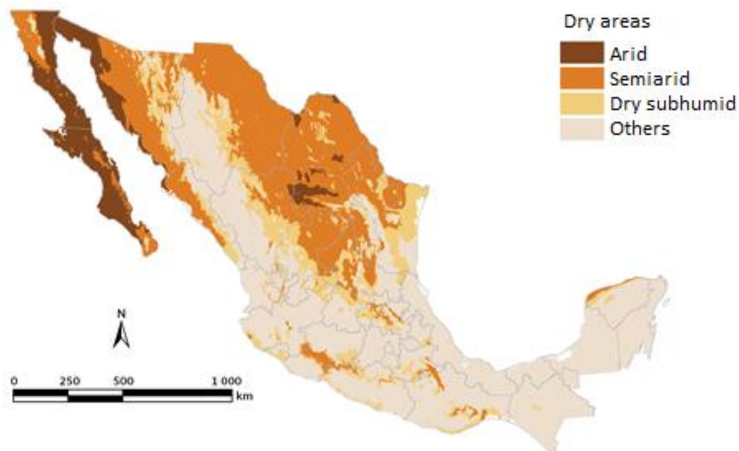

Figure 2. Map of Mexico and dry areas. Source: SEMARNAT (2012) [9]

Hence, DAD technologies can be applied in these regions without compromising water resources. At the same time, experts in the field remain to demonstrate the applicability of large-scale DAD digesters to treat rural and municipal organic residues in these countries. Hence, this research shall attempt to demonstrate the feasibility of medium and large-scale dry AD plants to treat municipal solid residues, considering the diverse conditions presented in Brazil and Mexico. The diffusion of DAD technologies is deemed necessary for the sustainable management and treatment of solid organic residues.

1.1 Justification

DAD systems (above >20% of total solids) are currently emerging for organic rural and urban residues treatment. They have been studied and implemented worldwide, principally in various European countries like France, Germany, and the Netherlands. Nevertheless, these technologies are still uncommon in agriculture [10], even when they offer considerable advantages and benefits over other organic treatment methods.

Stakeholders in Brazil and Mexico have not significantly developed the idea of large-scale DAD plants to treat solid organic residues. However, these technologies have been lately calling the attention of researchers and policymakers. The continuing diverse water and environmental problems in these countries demand a more determinant scheme for implementing such technologies and faster diffusion as an affordable large-scale organic waste treatment method.

DAD is a promising alternative, particularly due to its low water requirements that is the main advantage of dry over regular wet biodigestion systems [11]. The digestion process is an energy and water-saving process, which does not require – or very little, depending mainly on the substrate conditions – the addition of water. Furthermore, its technical simplicity, smaller reactor volume, and easy handling of residues are other advantages of dry systems. According to Arelli et al. (2018) [12], DAD could present in some cases even higher methane production rates than wet processes [11].

DAD technologies can also offer other environmental and socio-economic benefits, such as high nutrient recovery [12], following the national environmental legislation Resolution N°498 for the production and implementation of biosolids, income generation in rural or poor communities, or GHG mitigation, among others, resulting in a high potential for their implementation. Their applicability as large-scale digesters in these countries remains to be demonstrated, which is the primary intention of this project.

1.2 Objectives and research question

The main objective of this research is to answer the following research questions:

- *What are the advantages and disadvantages of DAD and WAD technologies for the treatment of OFMSW in Brazil and Mexico, and;*
- *How to foster the implementation of dry anaerobic digestion technologies for treating the organic fraction of municipal solid waste in Brazil and Mexico?*

To answer this question, this research pursuit the following specific objectives (SO):

SO1: To understand the state of the art of OWtE technologies in Latin America and the Caribbean countries, and – more specifically – the status of DAD in Brazil and Mexico;

SO2: To determine the technical and environmental benefits and disadvantages of DAD and WAD technologies:

- **SO2.1**. Based on two case studies, to estimate how much can large-scale DAD and WAD technologies benefit waste management, water savings, and energy systems in Brazil;
- **SO2.2.** To evaluate and determine what is the GHG mitigation potential of the studied DAD and a WAD treatment plants in Brazil;

SO3: To propose the policy guidelines for implementing AD, and more specifically DAD technologies, based on the existing regulatory framework in Brazil and Mexico.

1.3 General Methodology

The proposed methodology adopts three different phases to reach the specific objectives: (1) Literature review of Organic Waste to Energy in LAC; (2) Dry and Wet anaerobic digesters technical benefits and disadvantages; (3) Policy framework for the implementation of AD technologies.

The methodological approach uses the mixed method research (MMR) intending to attend the main research question through these multiple research phases and attend the specific objectives, using numbers and words.

MMR is intuitive reasoning and uses qualitative and quantitative approaches to better analyze and respond to the research question than just one method alone, achieving a greater understanding of the target topic and attaining consistency throughout the project objectives and phases. In brief, it combines quantitative and qualitative concepts and approaches, which allow understanding the study more fully [13].

According to Greene et al. (1989) [14], there are five primary purposes of MMR according to the research design: Triangulation, complementarity, development, initiation, and expansion; are based on the integration of quantitative-qualitative data and analysis. With these, MMR also helps to increase the validity of the research. Hence, the following methodologies described for each phase are complementary, and the results from one helped develop and inform another.

The proposed phases in this project are sequentially and uncover synergies and contradictions from one method to the other when presented. Hence, the diverse methods and approaches, mentioned with different strategies, helped obtain information for the results to be complementary, consistent, and well organized. This approach allows for results based on additional research perspectives and evidence. It also allows the results to document the outcomes and reach audiences, including public policy specialists, decision-makers, practitioners, and others.

Table 1 summarizes the data collection techniques, analysis approaches, and research objectives of each of these three phases.

Table 1. Data collection techniques, approaches, objectives, and characteristics of the research

SO	Research Objective	Approach	Tools	Data	Method	Data sources
1	Literature review	Qualitative	Documents and archives	Secondary	Archival Research Method	Scientific databases (i.e., Scopus, Science Direct, Web of Science, etc.), and publications from international institutions
2.1	Material Flow Analysis of water, waste, and energy systems	Quantitative Case studies	Interviews, questionnaires, and tabulators	Primary	Questionnaire	Company´s researchers and specialists
			Documents and archives, Life-Cycle Inventory STAN 2.6 Software	Secondary	Archival Research Method	Technical reports, publications, meeting minutes, and previously collected measurements
2.2	Potential mitigation of GHG emissions	Quantitative Case studies	Interviews, questionnaires, and tabulators	Primary	Questionnaire	Company´s researchers and specialists
			Documents and archives, Life-Cycle Inventory	Secondary	Archival Research Method	Technical reports, publications, meeting minutes, and previously collected measurements
3	Perspectives and relevant policy instruments for implementation of AD systems	Qualitative	Interviews and questionnaires	Primary	Structured questionnaire	Key actors and specialists (researchers, policy specialists & governmental officials)
			Policies, regulations, reports, forums, online conferences, and documents	Secondary	Archival Research Method	Governmental and non-governmental organizations, public and online libraries, and websites

2 LITERATURE REVIEW

2.1 Anaerobic Digestion

Today, researchers and decision-makers have used anaerobic digestion as a biochemical treatment for different types of urban, industrial, and agricultural waste and effluents throughout the world. They uphold numerous advantages over aerobic processes such as energy generation, lower sludge generation rate, emission reduction, and greenhouse gas reduction, among others that characterize it as a technology with a positive energy balance [15]. Following a general description of these technologies and their characteristics:

2.1.1 Basics of the AD process

Anaerobic digestion is a biochemical process that involves the decomposition of organic matter (OM) by microorganisms in an oxygen-free environment. These microorganisms degrade the organic material, with ultimate products mainly being methane (CH_4), hydrogen (H), and carbon dioxide (CO_2). These series of metabolic interactions occur naturally in low-oxygen niches such as marshes, sediments, wetlands, and in the digestive tract of ruminant animals and certain species of insects.

Anaerobic digestion occurs when bacteria break down organic material throughout four major biochemical processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 3).

- Hydrolysis: Large protein macromolecules, fats, and carbohydrate polymers (such as cellulose and starch) are broken down through hydrolysis to mainly amino acids, long-chain fatty acids, and sugars.
- Acidogenesis: Fermentative bacteria convert these products to form carbon volatile fatty acids (VFAs), ammonia, and other minor products such as carbon dioxide and hydrogen.
- Acetogenesis: In this step, bacteria consume the already fermented products and generate acetic acids, carbon dioxide, and hydrogen.
- Methanogenesis: Finally, methanogenic organisms consume acetate, hydrogen, and some carbon dioxide to produce a mixture of mainly methane and carbon dioxide. Acetotrophic methanogens utilize acetate as a substrate in a process known as acetotrophic methanogenesis. In a hydrogenotrophic methanogenesis process, the hydrogenotrophic methanogens reduce CO_2 by using H_2 as an electron donor. Lastly, in methylotrophic methanogenesis, methylotrophs microorganisms reduce one-carbon compounds, such as methanol or methane.

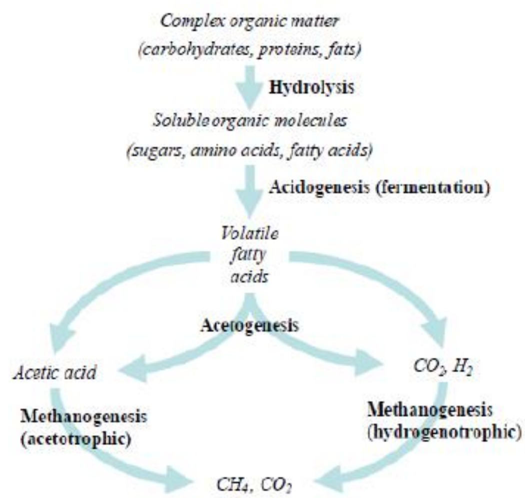

Figure 3. Anaerobic digestion, biochemical conversion pathways. Source: [16]

Throughout this process, biogas is produced, nutrients are conserved, and the pathogens in the organic matter are usually reduced. The essential nutrients for the bacteria to activate are nitrogen and carbon (C/N ratio), which must be available in a proper ratio for the best degradation rates. Carbon constitutes the energy source for microorganisms, and nitrogen serves to enhance microbial growth [17].

For digestion to happen, a wide variety of microbial communities is involved in the anaerobic decomposition process. Clostridium species are the most common among the degraders; however, it is very unusual for the biological treatment to rely solely on a single microbial strain. Generally, a microbial consortium is responsible for the anaerobic digestion process [18]. Hence, a group of other bacteria and archaea are involved in the degradation processes; *Methanosarcina* and *Methanobacterium* mainly contribute to methane production. Aside from this, different factors such as substrate and co-substrate composition and quality, environmental factors (temperature, pH, and organic loading rate), retention time, and microbial dynamics contribute to the efficiency of the anaerobic digestion process [19].

The composition of biogas varies with the type of feedstock and operating condition of the digester. In general, biogas consists of 50–75% CH_4 and 25–50% CO_2 along with other trace components like water vapor (H_2O), hydrogen sulfide (H_2S), and ammonia (NH_3) [20]. Methane is the main gas that can be burned and used to produce energy (H2S also contains certain energy potential).

AD can be generally divided into four stages for energy production purposes: Pre-treatment, organic material digestion, gas recovery, and residue treatment. Pre-treatment is usually a separation of non-digestible undesired materials, grinding, and mixing of the organics. Consequently, the biogas is obtained and stored for its use. Lastly, the digestate residue is dewatered and used as a composting product.

2.1.2 Types of AD reactors

Several types of bioreactors are currently in use; according to Khalid et al., 2011 [19], the three most common types of bioreactors include a one-stage (batch reactor or continuously fed system), a two-stage continuously fed system. Vandevivere et al. 2003 [21], among other scientists, also consider the water content of the solid waste on their categorization as "low-solids or wet" and "high-solids or dry". Several other authors also take the operational temperature into account as mesophilic or thermophilic processes. Hereafter, the research presents a broad overview of the most viable methods/types of biodigesters for agricultural and municipal solid wastes and their configuration to achieve considerable biogas production yields, presented in Figure 4:

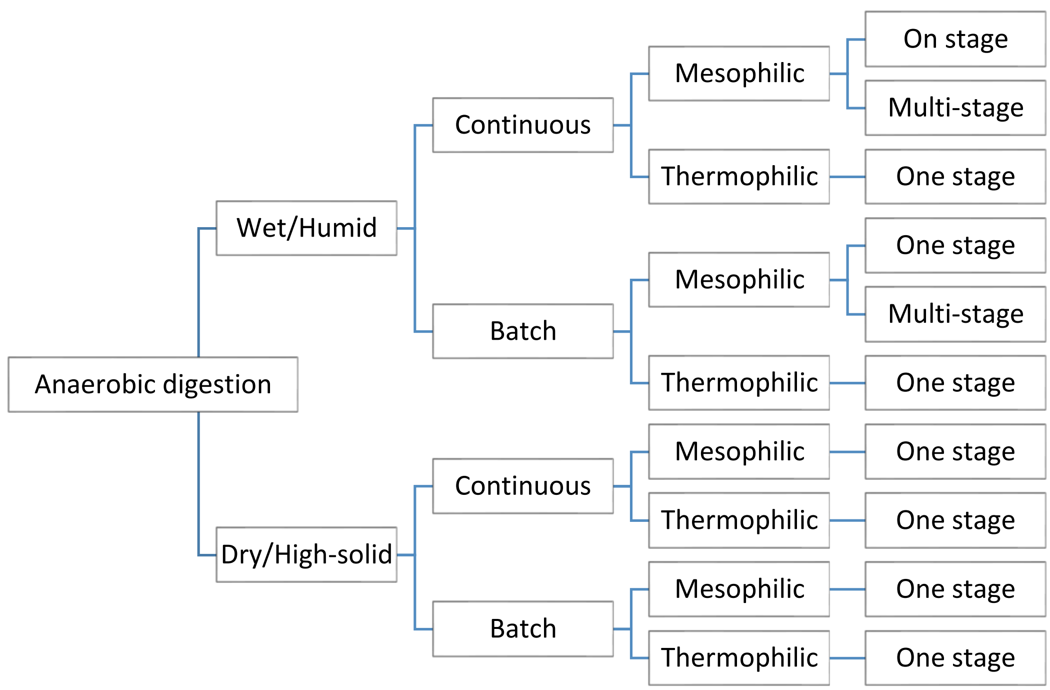

Figure 4: General classification of AD types. Source: adapted from IBTech, 2020 [22]

2.1.2.1 Wet/Dry

Biodigesters are primarily classified as ''wet'' or ''dry'', mainly depending on the total solids' contents of the substrates. WAD contains less than 20 percent of TS, although there is no established standard for the cut-off point. DAD is also called a high solid system, with TS content greater than 20 percent [16].

The rural and urban sectors have used wet systems for years, mainly for treating agricultural liquid or semisolid residues and municipal wastewater. In wet systems, the biodegradation of solid organic waste usually requires water to be added to the ground material to flow through the AD system [17]. These systems can use processed water, but this may also result in the buildup of inhibitory compounds [16]. On the other hand, dry systems usually appear to be more robust as frequent technical failures occur with wet fermentation technologies due to sand, stones, plastics, and wood, which block the systems [21]. For dry systems, the digester contents are usually kept with TS between 20 to 40 percent [16].

From a financial viewpoint, the two systems are comparable, although dry designs may require more expensive equipment [21]. The challenge of dry systems is handling, mixing, and pumping the high-solids streams rather than maintaining the biochemical reactions [16]. Thus, the two systems present advantages and disadvantages, which researchers must evaluate according to every region's local condition and waste composition. This research project attempts to develop on this matter.

2.1.2.2 Batch/continuous

AD technologies as a waste treatment method target the full potential of organic waste or biomass arising from municipal facilities through batch fermentation or a two-stage or multi-stage process. These systems are currently in use and offer different assets. Batch reactors are usually more straightforward, easy to maintain and operate, and lower capital costs; however, they can only produce limited biogas [23].

The general principle of batch digesters is to incubate biomass with an inoculum containing a variety of anaerobic microorganisms in a fermentation container over a pre-defined period. The process is used for energy crops, OFMSW, and other agricultural residues [24], and the four-digestion biochemical reactions occur in the same airtight digester. There is also a neutral pH and a specific temperature range (normally mesophilic) throughout the digestion process. Other primary operations merely involve seeding with inoculum and, in some cases adding alkali to maintain pH. Batch processing of solid material prevails in agricultural dry digestion systems [10]. This research further describes these systems in section 2.2.2.

Continuous digestion, on the other hand, function with the addition of residues to the reactors and constantly removing an equal amount from the outlet of the systems. Digester contents are not thoroughly mixed and move as a plug throughout the reactor entering from the port until the exit of the system [25].

These processes can handle dry, viscous, and course materials that do not flow freely, maintaining a minimum of 20% solids in the tank. They present diverse arrangements and, according to André et al. (2017) [25], can be grouped according to the stirring of the matter and forward to the system:

- The stirring is by recirculation of the digestate and the substrates deposited by gravity (Dranco technology);
- The stirring is by recirculation of the biogas and substrates are forwarded by a piston-based system (Valorga, Arkométha);
- The stirring is mechanical, and the substrates delivered by compression (Kompogas, Laran, Ineval, Eisenmann, CH_4 Systèmes);
- Without stirring (Transpaille, Easymeth).

Other advantages of these systems are the high and constant organic loading rate, and less solid/digestate retention time, hydraulic retention time [11].

There are already numerous types of batch single-stage and continuous digesters for commercial developments. The most used reactor designs for batch and continuous DAD systems are vertical and horizontal shapes, further described in section 2.2.2.

2.1.2.3 Mesophilic/thermophilic

The operational temperature affects the performance of digestion processes. Mesophilic temperatures range ideally from 30°C to 38°C, while the thermophilic from 44°C to 57 °C [17]. In terms of applicability, even though there are several references of successful operations in both temperature ranges, mesophilic digestion has always been predominant, mainly because it is the temperature of choice for most applications in wastewater, manure, and sewage sludge digestion [26]. It also has been demonstrated to provide good stability and constant gas production. Additionally, as cited in Hilkiah et al. (2008)[17], Tchobanoglous et al. (2003), biological reactions occur optimally and also provide stable treatment in the range of 25°C to 35°C. In the case of thermophilic digestion, it is a process that has always also played an essential role in the market, demonstrating to be an efficient method. According to De Baere (2012) [26], this technique usually increases biogas generation, especially in dry digestion. The disadvantages are the maintenance of high temperatures and the implicated higher costs. To moderate these temperatures usually extra heating is necessary, however in some regions of the world ambient temperatures are enough to reach at least optimal mesophilic conditions.

2.1.2.4 Single-stage/Multi-stage

In single or one-stage systems, as in batch reactors, all biochemical processes occur in a single reactor. In multistage systems, the reactions occur sequentially in at least two reactors. Single-stage systems are generally simple to design, build, operate, and less expensive. The organic loading rate of these digesters must be limited by the ability of methanogenic organisms to tolerate the decline of pH resulting from acid production during hydrolysis. The majority of the industrialist prefer them because they also present less frequent technical failures and have smaller investment costs [21].

Multi-stage anaerobic processes are characterized by segregating bacterial and archaea groups (i.e., acidogenic, acetogenic, and methanogenic) on their optimal biochemical conditions to optimize biogas production. Usually, it is a two-stage process; the first one harbors hydrolysis and acidification reactions, and the second one occurs the acetogenesis and methanogenesis reactions [21].

Two or Multi-stage processes are scarce [27] and commonly used for wet process reactors, treating feedstocks with between 2% and 12% of total solids, due to the better manageability of the residues than the dry case. Various systems are employed, although the most common is a mixing system by paddle stirrers that rotate vertically in a circular motion. The liquid digestate is usually recycled from the second vessel to the first to dilute feedstock and balance the system.

Compared to single-stage batch systems, two- or multi-stage processes are more rapid and stable; however, their higher investment costs make batch systems more financially viable. Even when multistage

DAD systems are more expensive to build and maintain, according to (Ward et al. 2008) in Karthikeyan & Visvanathan (2012) [11], the total CH_4 yield is higher enough to offset the cost factor. Further laboratory-scale studies can be appropriate to compare both processes considering that factors such as the types of residues, fluctuations of OLR, waste heterogeneity, and others cause variance in the performance of the digesters.

2.1.2.5 Other considerations

This research shall consider other factors considering the general characteristics of the digesting material, the rate of waste generation, microbial dynamics, and the local environmental conditions [17]. Present the following additional considerations:

- Hydrogen (pH) concentration control: The level and variation of pH in the organic material affect the anaerobic-digestion process. Sufficient alkalinity must be available at all times, up to a level of approximately 3000 mg/L, to maintain a high methane production rate. Various researchers have reported a range of pH values suitable for anaerobic digestion. Others have found that the optimal pH for methanogenesis to be around 7.0 [19].
- Carbon-nitrogen ratio: This is a determinant factor for microorganism reproduction. While carbon constitutes the energy source for microorganisms, nitrogen serves to enhance microbial growth. The optimal operation ratio of the carbon-nitrogen should be about 30:1 in the raw material. An optimum level can also be buffered, adding up manure, urea, biosolids, among others.
- The moisture content of the waste in the digester: Water content in the mixture is essential for decomposition and effective anaerobic digestion. Further, Vandevivere et al., (2003) [21] states that residues kept in their original solid-state (already containing water) can achieve the same biogas yields as wastes diluted with water.
- Waste-particle size: In the case of the particle size of MSW, treatment plants can shred or grind the organics to improve the digestion efficiency by presenting a larger surface area for bacteria decomposition.
- Mixing: Uniformity on the substrate concentration, temperature, and other environmental factors must be maintained, which could be done mainly by recirculating the produced gas or via mechanical agitators, depending on the TS concentration in the systems.
- Costs: Construction and maintenance of the plant costs are significant in selecting the right type and dimension of the bioreactor. The cost of pre- and post-treatment also has to be considered.
- Loading rate: The loading rate of organic materials into the digester indicates the total amount of volatile solids to be fed into the digesters every specific time. It depends on the characteristics of the digesting material since it determines the level of biochemical activity in the digester. The system achieves equilibrium when the food substrates and the microorganisms consuming them are in balance. The parameter to measure this equilibrium is the food to microorganism ratio (F/M).
- Pretreatment of waste: This is the preparation of the waste for the anaerobic digestion treatment. Necessary steps may include Magnetic separation, size reduction, drum screening, shredding, pulping, gravity separation, water addition, or pasteurization. Investors also need to carefully

review the selection of each option since pretreatment technologies add significantly to the system´s capital costs.

2.1.3 Large-scale AD in Brazil and Mexico

In the last years' large-scale digesters have gained inertia in both countries and been implemented, based mainly on CSTRs, UASBs, and cover lagoons. Hereafter, a general description of their progress in Brazil and Mexico.

2.1.3.1 AD in Brazil

Biogas production in Brazil has been incentivized and growing due to the latest regulatory advances in the country. On average, in 2020, around 1.83 billion Nm^3 of biogas were generated in Brazil, which is 23% more than the previous year [28]. According to CIBiogas 2021 [28], this energy comes from 638 biogas plants using urban, agro-industrial, and livestock waste. It is equivalent to around 2% of the National biomass capacity, which is 82 billion Nm^3, according to ABiogas [29]. Moreover, 543 units in Brazil had been generating electric energy from biogas with an approximate production of 1.32 billion m^3/day of biogas; this accounts for 73% of all energy generated from biogas [28].

Furthermore, specialists expect biogas generation to contribute even more to the energy matrix, considering that in 2017 the energy plan included biogas in the electric power expansion plan for the first time and the recent ratification of RenovaBio, which is the energy ministry's program for the development of biofuels industry. This data demonstrates that biogas potential in Brazil is high due to the large generation of OW. The CO_2 avoided emission may be up to 19.8 Mt CO_2/year., approximately 5% of the National emissions [30].

At the same time, several studies have been carried out in the country to test the potential of anaerobic digestion from various sources: For example, Konrad et al. (2014) [31] studied biogas generation from swine manure, using residual glycerin supplementation. Results showed that residual glycerin has significant potential to improve biogas production. Goulart, Coelho, and Lange (2018) [32] performed a life cycle assessment (LCA) in Rio de Janeiro to assess and compare eight municipal solid waste management strategies. Results indicate that the current situation of MSW presents the worst performance in terms of environmental burdens, and the scenario-based on recyclables recovery and anaerobic digestion resulted in the best strategy to improve environmental sustainability. Mersoni and Reichert (2017) [33] in the city of Garibaldi, Rio Grande do Sul, also compared various alternatives of treatment and final disposal of MSW (recycling, composting, anaerobic digestion, and incineration) under the environmental aspect through the LCA technique. Results demonstrated that the scenarios that contemplated organic waste treatment with anaerobic digestion (energy recovery) and composting, presented the best environmental performance. Research by Janke et al. (2014) [34] assessed the biomethane production potential of waste generated by the sugarcane industry in São Paulo State, Brazil. Results showed a biogas yield of 486, 647, 528, and 395 NmL/gVS, respectively, for filter cake, vinasse, bagasse, and straw. Using these residues for biomethane production could significantly substitute natural gas consumption. In São Paulo, according to the author, it could replace 10% of the natural gas with the utilization of filter cake, 17% with vinasse, and up to 54% with a fraction of lignocellulosic wastes (1/4 bagasse and 1/2 straw).

Other studies [35][36][37][38][39][40][41] have also evaluated the potential of the resulted vinasse from sugarcane and vinasse from corn and cassava production [42] as an alternative source of energy generation via up-flow anaerobic-UASB or with immobilized biomass [43]. They have found out that using vinasse as an energy source has great potential for energy production in Brazil. Hence, this stillage can be used as a source of renewable energy and still be used as a fertilizer for crops, considering that the treatment helps to improve the residues' characteristics and reduce the environmental risks when disposed untreated. Vinasse is the liquid waste generated during sugarcane ethanol production in an average of 10 to 15 liters for each liter of ethanol. There is currently a total production of 300 billion liters of vinasse per year in Brazil [36]. According to Bernal et al. (2017) [40], a total of 3.26 TWh/year of energy potential might be reached using these residues, representing 0.52% of all domestic energy consumption in 2014. The potential to avoid emissions by this method could get 1.9 Mt CO_2/year, approximately 2.1% of the emissions for the whole industry in Brazil in 2014. Urban transportation can also use the biogas generated by the AD of vinasse as vehicular biofuel. This opportunity presents an appealing use of biogas to supply transportation trucks within the treatment plants [44]. From a general perspective, adopting AD of vinasse technologies could lead to energy, environmental and economic profits [37]. However, Moraes et al. (2014) [38] highlights the main challenges that have inhibited the establishment of full-scale AD for vinasse treatment in the Brazilian sugarcane biorefineries, such as The unsatisfactory results obtained in the few large-scale anaerobic reactor plants; the predominance of empirical approaches in the fundamental studies of anaerobic digestion of vinasse; the lack of basic engineering information and the lack of valorization (environmental and economic stimulus for investment) of biogas as an alternative energy source. According to the author, increasing efforts from the scientific community will help change some obsolete concepts of AD vinasse treatment. Together with further fundamental engineering knowledge may boost the complete application of these processes.

More recently, in the Metropolitan Region of Ribeirão Preto municipality, the Companies Raízen, Sebigas-Cótica, and GeoEnergética merged to construct the first AD plant that will treat vinasse together with filter cake, attempting to prove the viability of such projects [45]. In addition, in Pirapozinho, there is a project in development to supply the city with biomethane produced with vinasse and other sugarcane residues [46].

In the state of Paraná, the first largescale co-digestion plant from organic solid wastes and sewage sludge is on operation, treating about 1,000 m^3 of sewer and 300 tonnes of organic residues. The plant has an installed capacity of 2.8 MW. In addition, a dry AD plant is under construction by the German Company Bekon in São Paulo with a capacity of 10,000 t/year and electrical power of 190 KW [47]. Also, in the city of Foz do Iguaçu, the CIBiogas institute developed a biodigestion plant to treat around half of tonne of biowaste daily, resulted from residues from restaurants and other organics; and in the city of Rio de Janeiro, the company "Methanum Resíduo e Energia" and Federal University of Mina Gerais (UFMG), built up a DAD treatment plant with a capacity to treat around 20 tonnes of OFMSW daily. This research project focused on these two treatment plants as study cases, further described.

2.1.3.2 AD in México

In Mexico, in the last years, some programs have emerged to provide financial and technical support for implementing AD systems throughout the country. Mainly through the state agency Sagarpa (Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food), several agribusinesses have been supported to install AD projects (primarily anaerobic lagoons) [48]. However, this has been limited to mainly treating animal manure for electricity generation. Rios and Kaltschmitt (2016) [49] suggest that stakeholders could collect and produce energy from other organic residues over the following decades.

In May 2017, the Company Suema and government officials inaugurated an AD treatment plant in Milpa Alta, México City, to treat various organic residues. With a production of 170 m^3 of biogas, equivalent to 175 kWh, and a production of 1 tonne of fertilizer daily production [50]. Also, in Culiacan, since late 2016, the first large-scale dry anaerobic digester was installed to treat agricultural waste with a capacity of 4,500 t/year and electrical power of 100 kW by the Company Bekon [47]. Another recent successful case is the AD plant built in Zitacuaro, Michoacán, producing biogas, electricity, and fertilizers from cactus plants [51]. Furthermore, various researchers carried out studies for the anaerobic treatment potential of other residues such as Nejayote (the primary by-product of the nixtamalization) [52], banana peel [53] and the vinasse produced during tequila [54] obtaining favorable results.

2.2 Dry Anaerobic Digestion

Among the currently existing diverse anaerobic digestion methods and plant types, dry anaerobic digestion is an up-and-coming technology, which has lately experienced increasing interest from researchers and policymakers. Their advantages to mainly treating residues with high contents of total solids (TS), practicality, robustness, suppleness make them a promising technology to treat the organic fraction of solid municipal and agricultural wastes and produce biogas. It is also gaining interest among decision-makers because of the increasing need for renewable energy production.

DAD technologies, also known as “high-solid” or “solid-state”, performs with processes that range within 20 to 40% content of total solids. Plants also use higher TS contents, although they commonly result in a limitation of the bacteriological activity, consequently lower biogas yields and higher risks of fungal growth. Whereas dry digestion has been implemented (mainly in Europe) to treat municipal solid wastes similarly to wet digestion, DAD processes are still uncommon to treat agricultural residues [10].

DAD can save significant GHGs emissions and lower environmental burdens, helping countries attain their national greenhouse gas reduction goals established by the NDCs under the new international agreement adopted in December 2015 in Paris [2]. At the same time, DAD technologies offer less water utilization since the substrates and inoculum themselves primarily contain the humidity necessary for the biochemical processes. Furthermore, as second-generation bioenergy technologies, the provision of waste materials does not require significant quantities of energy input or additional land, in contrast to first-generation agricultural biofuel production [5].

Moreover, aside from significantly contributing to reducing GHG emissions and the dependence on fossil fuels, DAD technologies can offer other benefits such as generating considerable amounts of digestate that has the potential to be used as fertilizer. Thus, generating extra income for farmers [10] and contributing to the nutrients cycle, especially considering nitrogen as digestion encourages transforming into bioavailable ammonia. Hence, the improved fertilizer value of the digestate represents an economic advantage of the AD plant [10]. DAD can be combined with composting for further treatment and other purposes such as land reclamation [55].

Hence, considering these and other socio-economic benefits, their implementation has a high potential, and their applicability as large-scale digesters in these countries remains to be demonstrated.

2.2.1 Total Solids and water efficiency; DAD vs. WAD

One of the main attractions of DAD technologies is that the quantity of water added to the raw waste processes is discarded or substantially reduced, hence minimizing the digesters' complexity and size [56], aside from other advantages hereafter presented. The total solids content is the utilized parameter to assess the water concentrations; hence, the relatively high TS contents (from 20% to 40%) in "dry" systems make fewer liquid effluents, resulting in considerable savings pre-conditioning and effluent treatment systems. Total solids value is one of the principal aspects that differentiate the type of digester technology and one of the main factors to be considered in designing a biodigester for municipal or agricultural residues.

Historically, reactors that operate processing materials with high water contents have been most common. Kusch et al. (2011) [10] explained that slurry was the predominant substrate for agricultural biogas plants throughout many decades. However, characteristics of the wet systems, such as the high water demands, the complexity of their systems, and ample availability of solid substrates after harvest, agro-industrial processes, and domestic uses, have lately made technologies such as dry anaerobic digestion more attractive. Hence, according to the author, technologies appropriate for high TS are imperative.

Some advantages of DAD over WAD systems, aside from the none or lower water requirements and less wastewater generation, include the following: Smaller reactor capacity requirements, robustness and fewer failures in the systems, less energy used for heating and agitation [12], less energy needed for dewatering, pumping and drying the digestate [57], no necessity to dispose of large amounts of liquid effluents [58], simplicity and facility to handle, minimum maintenance requirements [24], minimal nutrient loss and fewer risks due to the floating fibrous materials on the top of wet digesters [11], and greater flexibility in the type of feedstock used [59]. In addition, a comparison of CH_4 yield between DAD and WAD by Brown et al. (2012) [60] determined that by using three lignocellulosic feedstocks (corn stover, switch grass, and wheat straw), no significant difference in yields was reported. Also, [10] proved the general efficiency and high methane yields of several DAD systems and reduced problems occurring due to fibrous materials floating on top of the liquid in wet digesters. Lately and importantly, DAD systems seem to be more economical than WAD because of: smaller reactor volumes, no internal mixing arrangement (for continuous stirring, which can turn into a disadvantage of DAD), ability to handle a variety of feedstocks, and attain maximum CH_4 yields [11]. Many other researchers have reported the successful operation of DAD technology in the digestion of various lignocellulosic feedstocks [61].

Furthermore, DAD systems also present some challenges and disadvantages that impede applying these technologies at commercial scales despite the several advantages. Some of these are:

1) A requirement of more significant amounts of inoculum;
2) Longer retention times;
3) Lack of control over biological processes [24];
4) Microbial communities' behavior complexity;
5) Accumulation of volatile fatty acids (VFA) and ammonia [57], mainly when biodigesters use lignocellulosic materials as mono-substrates, or food waste;
6) No mixing is supplied [61];
7) In some cases high demands on technical equipment (e.g., stirring devices, pumps) due to the high viscosity of the substrates; not in garage types reactors where only a wheel loader is needed;
8) Increased odor emissions;
9) Higher risk for a shortage of micronutrients resulting in their addition [10]; and
10) higher organic loading rates [11][12].

Hence, further research efforts are needed to understand, address and tackle some of these drawbacks.

Regarding the high concentrations of total solids in DAD, several researchers have studied the systems' performance and methane production yields. For instance, Abbassi-Guendouz et al. (2012)[56] compared a range of TS contents from 10% to 35% and concluded that methane production slightly decreased with TS concentrations increasing from 10% to 25%, reaching a threshold at 30%, above which methanogenesis was strongly inhibited. Above this rate, there was an inhibition of methanogenesis. This result is consistent with Fernández et al. (2008) [62], who carried out a similar experiment where the methane production at 30% TS was 17% lower than 20% TS. Moreover, Forster-Carneiro et al. (2008) [63] showed better performance of reactors operated at 20% TS than 25% and 30% TS. Thus, these results suggest a reduction in substrate degradation and biogas production due to the mass transfer limitations with high TS contents. The specific methanogenic activity is consequently also reduced with high TS contents, as proved by Hyaric et al. (2011) [64]. They showed that activity decreased by a factor of 3.5 when moisture content decreased from 82% to 65% (18-35% TS, respectively). This characteristic brings some difficulties to dry anaerobic digestion and presents one of these systems' main challenges.

The rheological behavior of the substrates is another essential factor, especially when there is a high TS concentration and more serious difficulty in mixing and homogenizing residues. Karim et al. (2005) [65] proved that in digesters fed with 15% manure, slurry produced about 10–30% more biogas when the substrate was mixed. Hence, when the concentration of TS increases in reactors, mixing becomes more critical for improving methane production.

The role of TS content is crucial. It needs to be understood for every case to optimize dry anaerobic systems, and further investigations are required to thoroughly understand their role in the behavior of the microbial communities [56].

2.2.2 Batch anaerobic dry digestion

According to their operations, researchers classify dry anaerobic digestion technologies as a batch of continuous or semi-continuous technologies to treat OFMSW. Further, this study describes the main characteristic of batch systems, specifically the so-called garage systems.

Batch technology systems for dry anaerobic digestion are an emerging technology worldwide, developed over the past 30 years, already into the markets mainly in Europe with varying degrees of success [24]. They represent a straightforward system [10], as they require less process control measures than continuous or semi-continuous technologies, being more robust and less susceptible to failure [11]. They typically run in 30% to 40% of TS [24] and allow the use of non-pretreated OFMSW, containing inappropriate materials such as plastics, glass, wood, stones, and others. A maximum content of 10% of these materials should be tolerated to maintain the system running efficiently [7]. The utilization of source-segregated organic residues improves the quality of the process, generating a digestate of usually acceptable quality as fertilizer. A bag ripper system shall improve considerably the efficiency to separate plastic impurities on the disposal of the OFMSW [7].

The box or garage shape methanization systems are usually constructed of reinforced concrete and characterized by their shape as tunnels or garages, operating in sequential batches. The horizontal containers are sequentially opened, emptied, and fed at once via a loader with solid substrates and leftover a predefined period for the whole methanization process.

Fresh wastes must be firstly prepared and then filled in the digesters at once and sequentially go through all degradation steps in the “dry mode” [21]. The generated leachate is usually recirculated and sprinkled on the new substrates and used as an inoculant, assuring at the same time the necessary humidity in the system. Usually, there is no agitation system within the digesters which is often one of the main limitations of these processes due to the stagnation of the substrates in the digesters. Recognizing this, Forster-Carneiro et al. (2008) [66] and Guendouz et al. (2010) [67] designed a novel DAD batch system with internal mixing for better treatment. According to Kusch et al. (2011) [10], in order to equalize biogas production the treatment plant system requires at least three batch-operated dry digestion reactors need to be run offset.

Once digestion is complete during the 4 to 6 weeks process timing, the material gets removed, and thus the process restarts with a new fresh load of substrate [27]. After the digestion period and before the opening of the reactor, ambient air is injected to eliminate the methane still present and thus minimize any explosion risk. Further, the resulting digestate gets removed from the digester. Depending on its quality, it could be sent directly for soil improvement as fertilizer or post-treated via composting to stabilize the material or ultimately be discarded in a landfill post stabilization.

Some of the limitations of batch DAD technologies are high fluctuations in biogas production and quality, biogas losses, restricted design (Linke et al. 2006) in Karthikeyan & Visvanathan (2012) [11], lack of control over the biological process, or uneven heat or mass transfer [68]. The lack of mixing also causes low system efficiency since potential inactive zone may form due to inhomogeneous conditions [10].

Together with the need for improved economics, these drawbacks have driven ways to mitigate these limitations and innovation of batch reactors in recent years. However, diverse stakeholders should devote more efforts to innovating inoculation, mixing, or leachate recirculation to improve these systems further [23]. In addition, researchers may consider two-stage systems to increase the loading of substrates and thus the whole process efficiency [23]. Batch digesters' features such as simplicity of design and operation, robustness, and lower investment cost make them attractive for developing countries [27].

2.2.3 DAD in the world

Many anaerobic digestion commercial facilities are treating organic solids (especially from MSW) worldwide. Europe contributes to more than 90% of the AD plants, from which 60% is via DAD processes [11].

There are several configurations and manufacturers of large DAD systems to treat organic wastes with varying conditions. The following Table 2 adapts this diversity from the classification carried out by André et al. 2017 [25], Walker et al. 2012 [69], and Yanran Fu et al., 2018 [70]. It presents the current batch and continuous digestion technologies that have undergone significant development. However, some of these technologies are still at the prototype stage and not yet commercialized at an industrial scale [25].

Table 2: Characteristics of current batch and continuous DAD systems. *Source: Table adapted based on André et al. 2017* [25] */ * Walker et al. 2012* [69] */ ** Yanran Fu, et al., 2018* [70]

		Country	Capacity (t/year)	Substrate	TS (%)	Reactor type	T (°C)	OLR (kgVS·m³/day)	SRT/HRT (day)	Methane Yield ($Nm^3CH_4/kgVS$)	Methane average
Batch Dry Digesters											
	Silo-type digesters										
	Certitude Energies	*France*	*29000*	*AW*	*Na*	*H*	*Na*	*Na*	*21*	*Na*	*Na*
	GAEC Bois joly	*France*	*1380*	*AW, FW, GW*	*25-30*	*H*	*37*	*1.5*	*70*	*Na*	*56*
	Chiemgauer	*Germany*	*900*	*AW,GW*	*40*	*H*	*38*	*Na*	*30-45*	*Na*	*Na*
	Container or garage-type digesters										
	Isman and Ducellier	*France*	*Na*	*AW,GW,B*	*Na*	*H*	*37*	*Na*	*Na*	*Na*	*Na*
	Naskeo-Methajade	*France*	*2310*	*AW,GW*	*25*	*H*	*35*	*1.9*	*60*	*Na*	*55*
	Bal Hybrid	*France*	*6500-90,000*	*AW, B*	*Na*	*H*	*40*	*Na*	*28-35*	*Na*	*Na*
	EARL Bois Guilbert	*France*	*1400*	*AW, GW*	*28*	*H*	*35*	*2.1-2.4*	*38*	*Na*	*50*
	Omnisolis	*France*	*5900*	*AW*	*25*	*H*	*37*	*Na*	*45-60*	*Na*	*Na*
	Bekon	*Germany*	*7500-40,000*	*B, AW*	*Na*	*H*	*37-55*	*Na*	*28-35*	*0.17 - 0.37*	*Na*
	Bioferm	*Germany*	*8000*	*FW, GW, AW*	*25*	*H*	*37*	*Na*	*28*	*Na*	*Na*
	Loock TNS	*Germany*	*7000-50,000*	*B, AW*	*Na*	*H*	*37*	*Na*	*Na*	*Na*	*Na*
	Kompoferm	*Germany*	*20,000-245,000*	*B, AW*	*Na*	*H*	*37*	*Na*	*21*	*Na*	*Na*
	Smartferm	*USA*	*4000-30,000*	*B, AW*	*Na*	*H*	*55*	*Na*	*21*	*Na*	*58-60*
	Aikan Technology	*Denmark*	*5000-30000*	*MSW, B, AW, GW, FW, OFMSW*	*Na*	*H*	*Na*	*Na*	*35-50*	*Na*	*70*
	Biocel	*Netherlands*	*1000-30000*	*B*	*Na*	*H*	*37-55*	*Na*	*21*	*Na*	*Na*
	Mobiogas Technology	*Austria*	*1000-4000*	*B, FW, GW*	*>30*	*H*	*37-55*	*Na*	*21-35*	*Na*	*Na*
	Muckbuster and Flexibuster	*UK*	*180-1080*	*OFMSW, FW, AW*	*Na*	*H*	*Na*	*Na*	*21*	*Na*	*Na*
	Portagester	*UK*	*5000*	*AW, GW, FW*	*Na*	*H*	*37-55*	*Na*	*Na*	*Na*	*Na*
	Ambiogas	*Italia*	*Na*	*OFMSW*	*>50*	*H*	*35-38*	*Na*	*30*	*Na*	*55-65*
	SEBAC	*USA*	*1404*	*OFMSW*	*Na*	*H*	*55*	*Na*	*21*	*0.34*	*Na*
	*Dicom TM**	*Australia*	*20,000*	*OFMSW*	*20–40*	*H*	*55*	*Na*	*12*	*0.17-0.44*	*Na*

	**MCT	China	Na	AW	10--20	H	35-37	Na	Na	Na	Na
Continuous Dry Digesters											
	Stirring by recirculation of the digestate and the matter forwarded by gravity										
	Dranco	Belgium	10,000–70,000	OFMSW	18-32	V	50-55	10--15	20	0.21-0.30	Na
	Stirring by recirculation of the biogas and the matter forwarded by a piston-based system										
	Valorga	France	20,000–350,000	OFMSW	36-60	V	37-55	10--15	20-33	0.21-0.30	Na
	Arkolia	France	2200	AW	> 18	H	55	7.9-7.5	22	Na	55
	Mechanical stirring and the matter forwarded by compression										
	Kompogas	France	20,000–30,000	OFMSW, GW	30	H	55	4.3	29	0.39-0.58	Na
	Laran	Austria	11,000–80,000	AW, B, OFMSW	15-45	H	37-55	Na	Na	Na	Na
	Ineval	France	11,000–28,000 AW	AW	20-35	H	55	10--16	Na	Na	Na
	CH_4 Systemes	France	9900	AW	25	H	37	Na	Na	Na	Na
	**Linde	Germany	Na	AW, OFMSW	15-45	H	37-55	Na	N/A	Na	55
	Without mechanical stirring										
	Transpaille	France	12000	B, FW	17.5	H	32	1--2	Na	Na	60
	Easymetha	France	Na	AW		H	37	Na	Na	Na	Na
	**Gicon Holding GmbH	Germany	8,000	AW, OFMSW	25	H	37	Na	35	Na	53
Na: Not available, FW: Food Waste, OFMSW: Organic Fraction of Municipal Solid Waste, GW: Green Waste, B: Biowaste, AW: Agricultural Waste, V: Vertical, H: Horizontal, T: Process Temperature; OLR: Organic Loading Rate; SRT: Solid/Digestate Retention time; HRT: Hydraulic Retention Time											

The commercial designs for the treatment of OFMSW, kitchen waste, and yard waste, most developed and prevalent, are Dranco, Kompogas, and Valorga (continuous). These currently have more than 75 facilities, 24 active for ten years or longer [25]. As for batch systems, Bekon is the most common, with around 46 operational treatment plants worldwide. The Linde process (dry, two-stage continuous process), and Biocel systems (dry, single-stage, batch processes), are also used in other parts of the world [11].

For continuous systems, operational processes have different configurations: The Valorga process uses vertical steel tanks, operating with between 25% and 35% of total solids, with a central baffle that extends through the center of the tank; The Dranco process also uses vertical design operating with 30% to 40% total solids in the reactor, and no internal mixing mechanism. Kompogas, same as Linde, are horizontal mechanically mixed-flow fermenters. Other relevant continuous designs are ISKA and ATZ using percolation fermenter systems [71].

Bekon´s biodigesters are garage-type digesters, are gastight buildings consisting of at least three reactor bays. BIOFERM and LOOCK systems are other examples of batch garage-shaped percolation fermenters [71]. Section 2.2.2 further describes these technologies.

Treatment plants have proven the reliability of these systems for MSW, and they have become a prevalent system in Europe. Currently, extensive research has compared the experimental conditions of these processes, both offering advantages, and disadvantages. Moreover Nizami and Murphy (2010) [72] compared various configurations to consider a proper digester design and suggested no conclusive system design for treating substrates with high solids. They recommended considering the substrates characteristics and reactors configuration for selecting an appropriate design; some substrates may require pretreatment to allow for a profitable biogas yield.

2.2.4 Large scale Dry Anaerobic Digestion in Brazil and Mexico

As for methanization via dry anaerobic digestion and considering the successful experiences in Europe, these technologies have lately called the attention of stakeholders in Brazil and Mexico. However, there are still some characteristics that hinder the implementation of such projects. The lack of selective collection and waste mixtures with inappropriate materials are barriers to implementing such technologies [15]. On the other hand, nowadays, European firms are the leading developers of such technologies, making their implementation difficult in these countries due to high investment and importation costs, reducing the economic feasibility of such projects.

Nevertheless, for example, in Brazil, the company “Methanum Resíduo e Energia” and The UFMG, developed a dry anaerobic digester project so-called “new national technology” for the treatment of the OFMSW, adequate to the particular conditions of Brazil [15]. This initiative already resulted in constructing the first extra-dry methanization system for treating organic waste in the region, a demo-scale plant to study the storage strategies, treatment, and uses of the biogas generated [73]. In Jacarei, São Paulo, a plant is under construction with a capacity of 10,000 t/year and an electrical power generation of 190 KW. In Mexico, a DAD plant constructed in Sinaloa, Mexico, treats agricultural waste with a capacity of 4,500 t/year; both plants were developed by the German Company Bekon [47].

2.3 Nationally Determined Contributions (NDCs)

Brazil and Mexico could also benefit from DAD technologies to attain national goals of GHG reduction established by the NDCs under the international agreement adopted in December 2015 in Paris (Paris Agreement). The NDC´s are the country contributions for the planet's global temperature not to exceed 2°C. In Latin America and the Caribbean countries, the interest is very high, with 26 countries that submitted contribution commitments. Fourteen countries presented only Intended Nationally Determined Contributions (INDCs), and twelve presented NDCs [74].

Together with land use, the energy sector, including energy generation, efficiency, and transportation, are the most frequently mentioned mitigation areas and are considered a priority to reduce GHG emissions. Hence, all the countries in the region have goals to increase the implementation of renewable energies. The energy sector's contribution to achieving these goals in LAC is of great relevance. Currently, LAC maintains lower per capita emissions compared to the other world areas; however, lately, there has been an increase in emissions [74].

In the specific case of Brazil and Mexico, both countries have ratified their commitment to NDC´s goals. They are under the implementation of programs and policies to achieve the set targets. Brazil is committed to reducing greenhouse gas emissions by 37% in 2025; and by 43% in 2030, below 2005 levels [75], which includes reduction on deforestation rates as well. As for the energy sector, officials suggest achieving these goals by increasing the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030. Biofuels, such as biogas, ethanol, and biodiesel generation, are already playing an important role [75], and policies such as RenovaBio are promising to increase this share.

Mexico has also adopted a commitment to carry out mitigation actions to reduce 22% of its GHG emissions by 2030, equivalent to a reduction of 210 Mt of GHG. To achieve this goal, the country committed to supply 35% of its energy grid with clean energy in 2024 and 43% by 2030. These goals include bioenergy as a renewable source to achieve these targets, promoting biodigesters, mostly in livestock farms [76].

3 THE STATE OF THE ART OF ORGANIC WASTE TO ENERGY IN LAC

3.1 Introduction

Throughout the world, diverse stakeholders have successfully carried out several studies and actions to apply OWtE technologies for managing and treating solid organic residues[2]. These practices have already been implemented in Latin America and the Caribbean (LAC) countries. However, there is still a long way to significantly contribute to managing and treating the ever-increasing waste volumes in the region, supply the regional energy demand, and meet national goals for carbon emissions. Hence, biowaste (i.e., household organic wastes and forest and agricultural residues) is still not sufficiently recognized as a valuable energy source with significant potential. As a result, it is mainly underused in the region.

OWtE technologies in the LAC countries differ from one country to another. For the last 40 years, local experiences have varied regarding implementation strategies and sectorial applications due to political contexts and technological changes. Some of the reasons that have not allowed the appropriate implementation of these technologies for biowaste treatment are high upfront costs, deficiency in access to sophisticated technology, lack of participation of stakeholders, and public policy deficiencies. This inconveniences sometimes results in severe environmental and health impacts due to lack of proper final disposal [77]. In addition, the continuing increase of electricity demand in the region has forced local stakeholders (e.g., farmers, waste managers, researchers, among others) to look for ways to optimize existing waste treatment options, which could allow energy recovery [4]. Thus, the idea of searching for and implementing affordable waste-to-energy (WtE) strategies has been lately gaining momentum and fostering debate on whether specialized technologies, such as thermochemical or biochemical, can assist in supplying local energy demands. Other essential benefits, such as improving nutrient recycling and avoiding the consumption of conventional fossil fuels, encourage the adoption of these technologies. Local projections expect biomass (e.g., biofuels) and biowaste to contribute to energy production significantly. However, the applicability of such projects for large-scale production remains to be demonstrated [78].

When this research started, a state-of-the-art literature review and a broad frame of literature reference were missing. However, the preliminary examination of the body of knowledge shows diverse literature related to OWtE in LAC, such as publications from the Network for Biodigesters in Latin America and the Caribbean (RedBioLac), academic papers from distinguished international journals, and other sources. Hence, the overarching goal of this research phase was to contribute to the development, adoption, and diffusion of technologies that generate social, economic, and environmental values from the use/treatment of organic residues in the LAC region by building a *state-of-the-art* of regional and current technological context.

To advance towards this goal, the present study has a twofold aim: On the one hand, it aims at systematizing the current state of knowledge about the technological and environmental situation of OWtE in the LAC context. On the other hand, it targets to identify knowledge gaps, challenges, and opportunities for further development and promotion of these technologies as tools for achieving the sustainability goals in the region, such as reducing carbon emissions under the Paris Agreement. It is

[2] As a result, this study does not cover biodiesel production, especially from waste streams.

essential to mention that this in-depth and descriptive literature review attempts to cover all aspects and facets of the matter from a regional context.

3.2 Methods

The research uses the Archival Research Method (ARM) to determine the state of organic waste to energy technologies in Latin America and the Caribbean. The ARM is a research strategy to examine previously recorded facts, which depend on the originality of the documents, primary and secondary official files, and records gathered by other investigators and researchers [79]. To accomplish an exhaustive literature review was necessary to cover an in-depth and wide range of publications. The ARM comprises the following steps:

i. *Defining database source:* the review covered well-established scientific databases (i.e., *Scopus*, *Science Direct*, *Web of Science*, etc.) and publications from renowned international institutions (i.e., United Nations Economic Commission for Latin America and the Caribbean, United Nations Environment Program, World Energy Council). The data collection was in three languages: English, Portuguese, and Spanish.
ii. *Delimitation of the scope:* the timeframe covered almost two decades, from 2000 until 2018, to include recent and historical publications.
iii. *Defining unit of analysis:* the review included single research papers, reports, books, and Internet articles. Other sources were Institutional websites, academic databases containing reports, MSc theses, and Ph.D. dissertations, among other sources of scientific publications. The selected research articles are from the top 25% of international scientific journals, according to the SCImago Journal Rank (SJR) indicator, based on the research topic related to waste, environment, and energy themes. The SJR rank is an indicator to measure the scientific influence of academic journals. It accounts for the number of citations received by an article and the importance or prestige of the journals from where citations come.
iv. *Sampling:* the first sample of documents resulted by searching the selected keywords and Boolean connectors: *lignocellulos** OR *organic* OR *biowaste* AND *waste** OR *residues* AND **energy* OR *biogas*. The first sample contained 21,024 publications.
v. *Applying regional filtering:* Later, there was a filtration of the collected documents according to the region of interest and considering all countries and sub-regions in LAC: North, Central, and South America, and Caribbean Islands. This step reduced the number of publications from 21,024 to a second sample with 482 documents.
vi. *Conducting a general compilation:* the documents from the second sample were then stored and organized to discard repeated information and avoid duplicity. As a result, the second sample was reduced to 342 publications.
vii. *Defining final sample:* the third sample used inductive analysis to classify the information by geographical scope and categorize it into two main topics: thermochemical and biochemical technologies. Then we carried out a sub-categorization of the specific type of technology (i.e., combustion, gasification, pyrolysis, anaerobic digestion, fermentation, landfilling, and microbial

fuel cells). After reading all abstracts and conclusions of each of the documents within the third sample, the documents containing very technical information (i.e., documents fully describing the biochemical process) and research articles (i.e., documents describing budget details) were discarded.

The fourth and final sample contained 199 documents and was sorted by country of interest. Figure 5 illustrates the sampling steps and the number of selected publications for each one of the steps.

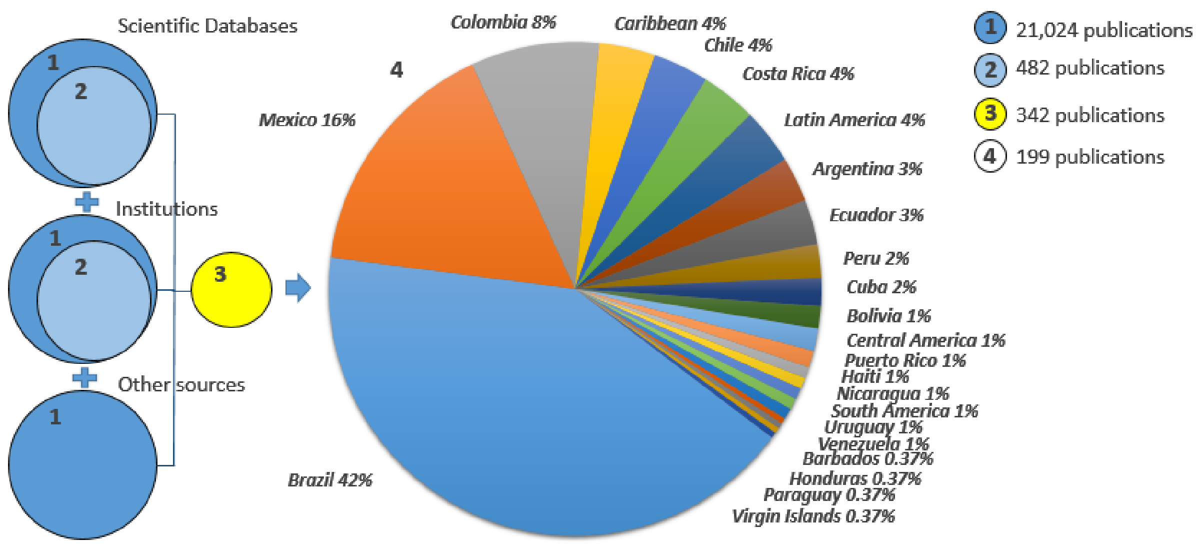

Figure 5: Sampling steps and number of documents for each step

Once the relevant documents were selected, we carried out a deep and detailed Content Analysis (CA). CA is a research technique used to make replicable and valid interpretations by systematically evaluating texts (e.g., academic articles, reports, and other publications) and converting them into valuable information that allows researchers to examine nuances of organizational behaviors, stakeholder perceptions, and societal trends [80]. The aim of using CA, in this case, was to collect information that is useful for understanding the current state of OWtE in LAC, viability, and the potentials of the thermochemical and biochemical technologies in the given geographical context, as well as observations about research gaps, opportunities and challenges. To achieve this, each document was read, analyzed, and coded, highlighting and selecting relevant pieces of information. The goal was to search for patterns and cluster observations into related subtopics to finally compare and synthesize their state in each sub-region and country.

3.3 Results; the current technological context in Latin America and the Caribbean

Every year millions of tonnes of agricultural, forest, and urban waste are generated in LAC. Several studies in recent years have presented technical, environmental, and economic analyses of different OWtE technologies and their comparative performances for bioenergy production. However, they are not fully explored in the region.

To facilitate the analysis and presentation of results, this review follows the technological classification established by the World Energy Council [81] to present the compiled information in two main technical categories a) thermochemical and b) biochemical processes.

Thermochemical technologies include combustion or incineration, gasification, and pyrolysis. Among them, incineration is the most commonly practiced in the region [82,83]. Nevertheless, there is an ongoing debate on whether this is the suitable organic waste treatment method, considering the adverse environmental effects and the low process efficiency these technologies portray compared to other treatments such as pyrolysis and gasification systems.

Biochemical technologies comprehend anaerobic digestion, fermentation, landfilling gas capture, and microbial fuel cell (MFC) technologies [81]. Research and Development (R&D) in the region has been primarily focused on small-scale anaerobic digesters (AD) [84] and landfilling. In addition, R&D has studied fermentation to a lesser extent. Interest in large-scale biodigesters, second-generation (2G) biofuels and MFCs has gained ground in Argentina, Brazil, Chile, Colombia, and Mexico.

3.3.1 Thermochemical technologies

Existing thermochemical technologies (e.g., incineration, gasification, and pyrolysis) use heat to promote transformations of biomass into energy and chemical products. On the one hand, these technologies follow similar processes to create three main products: solid (e.g., char and ash), liquid (e.g., bio-oil or tar), and gas (e.g., syngas or producer gas). On the other hand, each process uses different reaction conditions such as temperature, pressure, heating rate, residence time, reactive or inert atmosphere, purge gas flow rate, among others [81].

Currently, incineration is the most used technology in the region. However, gasification and pyrolysis present some advantages, such as a more thermally efficient and flexible system for utilizing downstream products (e.g., biofuels, chemicals, or fertilizers) [85]. The decision for selecting any of these technologies is related to:

- The diverse type of residues or lignocellulosic materials treated;
- The developed energy carries; and
- The local interest.

For example, direct combustion can produce steam to generate electricity. Gasification produces a lower heating value gas, which power gas turbines can use [83]. Furthermore, Parascanu *et al.* (2017) concluded that for pyrolysis processes, the desirable characteristics of biomass are high volatile matter with low ash content. For combustion processes, the biomass must show a high low heating value (LHV) combined with low ash content. In the case of gasification processes, the biomass ought to have high fixed carbon[3] [86]. The implementation of thermochemical technologies might be present in the upcoming years because they show a possible pathway for using urban residues in various regional countries. Significantly, the development of small-scale commercial systems (e.g., gasification) for the production of power in rural areas and small municipalities [83].

3.3.1.1 Combustion or incineration

Combustion technologies, also referred to as incineration (when using MSW), have been implemented in the LAC region as an alternative for waste or residue treatment. Diverse countries in the Caribbean Islands utilize biomass from agricultural and forest residues to produce electricity through combustion techniques. Countries like the Dominican Republic [87] or Cuba practice combustion technologies to produce energy from organic residues such as sugarcane straw and bagasse, rice husk, coffee husk, and firewood [88]. Most of the urban waste in the British Virgin Islands is incinerated, despite the high costs involved [82]. Conversely, in other countries of the sub-region, such as Puerto Rico, there are no incineration plants, and urban waste is landfilled or recycled [82].

In the case of Central America, currently, sugarcane bagasse and straw are the only agricultural residues to produce energy at a large scale [83]. Almost half of the existent sugar mills in the sub-region produce heat and power through combustion processes (e.g., combined heat and power (CHP) plants), supplying electricity to the region [83]. In Belize, there is a cogeneration power plant using sugarcane bagasse as fuel, with an installed capacity of 31.5 MW [89]. In Guatemala and Honduras, these treatment processes play a significant role in electricity supply [90]. Around 67% of sugar mills in Guatemala and 100% in Honduras operate under CHP schemes firing bagasse [83]. Regarding scale, Nicaragua holds one of the largest sugar mills in the region; The San Antonio sugar mill is the top electricity producer from sugarcane bagasse in the region, currently with an installed capacity of around 79 MW [91]. In Mexico, there are approximately 59 projects for self-power supply through combustion processes using biomass residues (i.e., mostly sugarcane bagasse) with an installed capacity of 500 MW [92].

In the case of South America, particularly in Brazil, bagasse from sugarcane is an essential source of electricity with an operating power potential of more than 9 GW [93], considering that burning bagasse is still by far the least cost option in comparison with other thermochemical routes [94]. Additionally, Brazil is one of the largest agricultural producers globally, with a large generation of agricultural residues [95]. It already has many biomass combustion power plants running on different feedstock beyond sugarcane bagasse. For example, black liquor (1,700 MW), wood residues (371 MW), rice husk (36 MW), charcoal (35 MW), elephant grass (32 MW), and palm oil (4 MW) [93]. In addition, the first thermoelectric plant for eucalyptus residues was already authorized, with a capacity of 50 MW in the State of Mato Grosso do Sul and should start operation by 2021. The owner of the thermoelectric plant is also planning to install two more plants shortly [96]. There is also a current plan to construct an energy recuperation unit in Barueri,

[3] Fixed carbon is the final calculation of the amount present in a biomass sample after the percentages of moisture, ash, and volatile matter have been determined.

São Paulo, to produce electric energy from urban wastes, with a combustion unit of 20 MW power capacity [97].

Other countries in LAC have identified their potential for applying local agroindustrial and forest residues as alternative energy sources in direct combustion processes. In Costa Rica, for example, the agricultural sector produces approximately 1.5 million tonnes of residues per year, mainly from bananas, coffee, sugarcane, pineapple, and oil palms. However, these residues are currently also in demand as a supplement for fodder. Therefore, a potential exists in using some percentage of these residues to generate heat by direct combustion of raw residues [98], without affecting the fodder demand.

LAC countries usually landfill their household solid waste residues without any pretreatment (e.g., sorting, recycling, and so forth); most of these residues can also be used as an energy recovery alternative to reduce the impacts of household solid waste (HSW). Various studies [99][100][101] have demonstrated HSW energy potential and technical and economic feasibility of the incineration process as an efficient way to treat it. Furthermore, a study by Nordi *et al.* (2017) demonstrated that removing the organic fraction of the HSW increases the efficiency of energy production [101]. Therefore, they suggest that incineration should not be a solution for treating the OFMSW. It is important to mention that the costs (e.g., upfront and operation costs) of incineration plants for HSW as an appropriate solid waste management technology [100] are still far too high in most countries in the region. For example, incineration in Suriname is not feasible due to its high costs and high humidity contents in the wastes [102].

3.3.1.2 Densification

Diverse densification techniques exist and have been applied in the region to promote better and faster combustion processes such as pelletizing, briquetting, and torrefaction, which help achieve adequate properties and a higher calorific value from the original materials. These pretreatment technologies also provide advantages such as increasing bulk density, reducing transportation, and storage costs, facilitating material handling [103]. For example, pelletizing wood residues can have an economically attractive opportunity for areas with conifer plantations. Densification can increase the heating value up to 22.13 MJ/kg and meet the requirements for high-quality pellets [104].

Even though the pellet industry is developing in LAC, there is still a large potential to pelletize agricultural and wood residues. Nowadays, Argentina [95][105], Brazil [95][103][106], Chile[95][107], Costa Rica[98][108], Honduras [95], Mexico [95], and Uruguay [105] produce pellets at industrial level for national markets but their exports are still insignificant [95]. Other countries show real potential to produce pellets [105], such as Colombia [95] [109] and Peru [110].

Even though countries have not established specific policies for the regulation of pellets production in the region, it is expected that the topic will advance in the years to come. Pelleting has lately called the attention of scientists and decision-makers in the region as an effective way of densifying the energy contained in lignocellulosic wastes and wood. Also, to significantly replace the direct burn of agricultural wastes that produce large amounts of gaseous pollutants harming the environment and people's health [95].

The cause for the currently small number of pelletizing industries and underutilization of wood residues in the region generally are The undeveloped national markets for wood pellets, lack of knowledge on technical and economic advantages of pellet production, competition with cheap natural gas, and costly transportation that creates a challenging environment for residual biomass logistics [95].

Studies from Gaitán-Álvarez & Moya (2016) [108] and Sánchez et al. (2017) [111] show that local potential for producing pellets from torrefied biomass (e.g., wood residues, avocado seeds, and husks) presents adequate properties and high calorific value. In the Dominican Republic, there have been governmental support for producing briquettes for their use in small and medium-size industries [87]. Furthermore, in Colombia, researchers such as Marrugo et al. (2019) state that using biomass residues in the form of pellets provides an opportunity to successfully incorporate a high-quality biofuel into the national agroindustry chain [112].

This research does not cover the analysis of Refused-Derived Fuel, mainly of combustible components (e.g., non-recyclable plastics not including PVC, paper cardboard, labels, and other corrugated materials) of various types of waste such as municipal solid waste, industrial waste, or commercial waste. The reason is that RDF has neglectable values of degradable organic residues in its composition.

3.3.1.3 Gasification

Gasification is the thermochemical conversion of an organic material (e.g., biomass) into a valuable gaseous product, called syngas, and a solid product called char [113]. There exist different types of gasifier configurations: downdraft gasifiers, which are the most often available commercially, followed by fluidized beds, updraft, and other gasifier types [114].

Gasification is an emerging technology in the Caribbean islands due to its various benefits [82]. Mohee (2015) [82] points out the following facts: in Aruba, the company *WastAway* patented a new technology for the conversion of unsorted HSW into a sub-product, which gets consequently gasified for steam and electricity generation [115]. In Barbados, Cahill Energy plans to implement a gasification plant to meet the country's target of replacing 29% of its oil-based electricity with renewables by 2029 [116]. In the case of Cuba, the first gasification plant was installed in 2010 using biomass as feedstock [117], producing electricity for 96 households, a bakery, a primary school, and a water supply system. Producing around 50,00 kWh of electricity annually, this small-scale gasification plant saves more than 18 tonnes of diesel fuel [118]. Furthermore, aside from agricultural and wood residues, gasification offers efficient energy outputs to treat other wastes such as medical and used oil, among others [82].

In Central America, there are no operating gasification plants and no plans to develop this type of project in the coming years [119]. On the one hand, the successful case in Cuba is a valuable experience for the future transfer of technologies for the design, start-up, and operation of small-scale gasification systems [83]. On the other hand, diverse stakeholders hall surpass various barriers such as financial, institutional, technical, and human resources to make these technologies technical and economically feasible [118].

According to Cutz et al. (2016), the sub-region can produce between 96 to 175 MW by implementing DGs and FBs gasification systems running with logging residues in Central America and up to 31 MW from agroindustrial residues. By combusting these residues, up to 150 MW could be produced [83].

Looking at South America, diverse experimentation indicates that gasification has the ideal characteristics for producing energy. For example, in Chile´s case, the potential of FBs gasifiers was found for the electricity production from wheat. However, these technologies have not been commercially available because they do not have a competitive price yet [120]. García et al. (2017) [121], in Colombia, also suggests improving the production costs that gasification has to be competitive with traditional technologies. This study also declares that gasification is the best technical scenario for hydrogen production and ethanol and electricity. In Mexico, the study by Rincón et al. (2014) [122] shows gasification as the most advantageous system to generate significant contributions of electricity and heat. Other countries such as Guyana have proposed these technologies as waste management technology. In contrast, researchers in Suriname have investigated the gasification of rice husk as a potential solution to the energy and waste disposal problem [82].

A research group at the Universidad Nacional de Colombia has designed and built a system for biomass gasification involving a fixed-bed parallel flow reactor. The results show good production of quality syngas from biomass such as wood, cocoa waste, coconut, and coffee husk [123]. The authors point out that projects in the future would allow commercial gasification systems in Colombia to produce low-cost energy; further research is necessary.

In line with this, Martínez et al. (2020) analyzed the gasification of corncobs for power generation in an 18kW pilot-scale fixed bed system under various conditions. They concluded that this residue is suitable for power generation, even with a content of up to 15% of fines [124]. Also, García et al. (2017) analyzed hydrogen production through the gasification of coffee cut stems. They argued that the process could potentially produce high H_2/CO ratios, but it needs to be benchmarked with other technologies and evaluated in the context of integrated biorefineries [121]. In Ecuador, Narvaez et al. (2013) [125] compared several WtE technologies that can be applied to manage solid wastes, highlighting gasification as the most promising in terms of potential power generation.

Brazil science has developed technologies for converting biomass into syngas through gasification in downdraft gasifier systems. According to Panwar et al. (2012) [126], this is the most appropriate system for industrial applications such as heating and drying of agricultural and industrial products. For example, in the Amazon, the electricity needs of isolated communities and small towns can be satisfied through gasification systems [127]. Moreover, this technology has already gained ground in the business sector in other parts of the country. However, no project has operated long enough to reveal accurate data to assess performance and costs [128]. Besides, researchers have also conducted complementary studies to evaluate the gasification potential of rice husk [129]. Other researchers have also detected the market´s potential for gasification technologies for agricultural residues in Brazil [130]. Alongside, there is currently a gasification plant under construction in the city of Extrema in the state of Minas Gerais with a potential capacity of 2 MW to process around 85 tonnes per day of MSW [131].

Conclusively, gasification is one of the most promising technologies for mitigation and generating energy such as heat, hydrogen, ethanol, and electricity. Among the potential benefits of biomass gasification are its use for waste treatment, reducing greenhouse gas emissions, fostering regional socioeconomic and agricultural developments, and offering a regular supply of energy, especially for isolated communities [127].

3.3.1.4 Pyrolysis

Pyrolysis is an effective and efficient thermochemical process in which bio-oil and inert gas result from the thermal degradation of the chemical constituents of the biomass. It is the previous stage of combustion and gasification [132] and comprises the thermal decomposition of material in the absence of oxygen. The primary benefit of pyrolysis, as compared to other technologies, is that this bio-oil can result in fuels for the transport sector (e.g., diesel and gasoline) or as feedstock for chemical industries [128].

Even when pyrolysis is the least thermochemical technology practiced in the Caribbean Islands, according to Mohee *et al.* (2015) [82], tentative cases are discussed, such as implementing a plant in Haiti. Here the produced biochar from agricultural residues could be employed to improve the soil quality, as well as to stimulate plant growth, and produced bio-oil to supply fuel in rural areas [133]. Also, pyrolysis has been proposed in other countries of the region such as Jamaica and Puerto Rico for managing used tires [134], or in Anguilla, where diverse stakeholders proposed a pyrolysis plant to reduce the number of wastes landfilled by 90% and supply 30% of the Island´s energy [135]. Also, in Saint Kitts, a plant with a capacity of 5 MW was proposed as a renewable energy alternative [136].

Countries in Central America, do not consider pyrolysis as a potential solution yet. This technology is considered the least preferable technology in the region because of the high investments and operating costs [83]. In addition, according to Cutz *et al.* (2016) [83], there are currently no plans to build any pyrolysis plants in the region. However, in the case of Mexico, a study by Gracida-Alvarez *et al.* (2016) [137] supports the implementation of this technology to produce renewable fuels in the country. The study results show that this technology can displace up to 7% of the current annual fossil fuel consumption in transportation.

In South America, Guyana, for example, employs pyrolysis to produce charcoal from wood [138]. Civilizations in the Brazilian Amazonia have used slow pyrolysis techniques to produce biochar as an energy-dense solid product [139]. Nowadays, other cases have occurred in Brazil. For example, “Bioware Tecnologia”, which is supported by the University of Campinas (UNICAMP), promotes fast pyrolysis [140]. Other studies have demonstrated the great potential and efficiency of pyrolysis treatments in countries like Brazil [141] [142] [143] [144] , Colombia [109] [132] [145], and Ecuador [146]. However, these studies point out that further research is necessary to understand its feasibility and logistical processes.

3.3.2 Biochemical Technologies

Biochemical, organic waste treatment technologies are based on the decomposition of organic matter under microbial action to produce biogas and digestate (e.g., biofertilizers). The conversion technologies utilize microbial processes to transform degradable waste such as food, forest, and agricultural residues [81] into biogas under anaerobic conditions. In recent years, these technologies have been developed and implemented in the region to various extents. Interest in large-scale biodigesters, 2G biofuels, and MFCs have gained ground in the region.

3.3.2.1 Anaerobic Digestion

The Research and development of organic residues' AD in LAC has mainly covered small-scale digesters, typically used to produce biogas for heating and cooking purposes [84]. The main reasons are the low investment cost and the low maintenance these technologies require, resulting in multiple successful biodigesters designs and the adoption of small-scale technologies [77]. Since 2009, the RedBioLAC has promoted and assisted the regional coordination of R&D programs. This Institution was established by the non-governmental organization Green Empowerment with support from the US Environmental Protection Agency and the Wuppertal Institute for Climate, Energy, and Environment.

It is relevant to mention that interest in large-scale biodigesters has been gaining ground in the last years in some countries (i.e., Argentina, Brazil, Bolivia, Chile, Colombia, Costa Rica, Mexico, Paraguay, Puerto Rico, and Uruguay). In the last decade, diverse countries in the region have researched treating residues via large-scale AD, with some interesting results on biomethane potential and techniques [147][148].

3.3.2.2 Small-scale digesters

Most small-scale digesters treat agricultural residues. Hence, this study assumes small-scale digesters as biogas plants with installed capacity below or equal to 100 kW while the large-scales digesters are above this threshold.

The first small-scale biodigesters were installed in LAC in the early 1970s. In the following decade, most of the countries in the region had developed experiences with these technologies. This process accelerated in the 1990s and early 2000s [77], and small-scale ADs have spread successfully in rural zones of Latin America. These low-cost anaerobic digesters are considered an appropriate technology that helps to expand modern energy services in developing countries, significantly increasing households' access to energy [149]. Additionally, implementing these digesters has proven to be an efficient way to improve sanitation and decrease illnesses and environmental impacts such as soil contamination [150].

The main types of small-scale biodigesters installed in the region are the fixed dome digester and the tubular Taiwanese model. However, the Taiwanese-model digester's low-cost and non-mechanized AD designs replaced the fixed dome in the late 1990s. Hence, Latin American countries have successfully treated agricultural residues, especially manure, since the first plastic tubular digester was introduced in Colombia in the late 1970s. Since then, the technology has spread in rural areas of the region, especially in Colombia, Costa Rica, Cuba, Ecuador, Honduras, Mexico, and Nicaragua [83][151]. Lately, research has been able to adapt this technology to harsh climate conditions of some Andean countries such as Bolivia [152], Peru [153], Chile [154], Ecuador, and Argentina [77]. In Brazil, small-scale digesters, known as “Sertanejo” biodigester, were based on the Indian model and implemented in the northeast region of the country [155]. Unfortunately, due to operational problems, many farmers had abandoned this technology [156]. There are, however, a considerable number of small-sized biodigesters, mainly in the south and southeast regions of the country [157]. Currently there are 406 biogas plants in Brazil, from the majority are small-scale plants using animal residues – mostly pig’s manure – as feedstock and producing electricity under the distributed generation system[4] [158] [159].

The Caribbean Islands present potential for implementing small-scale AD technologies because the organic fraction in the region averages around 44% [82] of the total MSW. Small-scale AD was introduced first in the English-speaking Caribbean countries by the German organization “*Deutsch Gesellschaft für Technische Zusammenarbeit”* [160]. In Jamaica, between 1988 and 1993, there was an installation of around 200 small-scale biogas digesters. In the case of Cuba, small-scale AD was introduced as early as 1940. Nowadays, there are hundreds of digesters installed in the country [82]. In Belize, a polyethylene digester for converting manure into biogas was installed in 2009 [161]. In Haiti, where the lack of essential sanitation services and inadequate waste treatment largely contributed to the ongoing cholera epidemic [162], small-scale AD is a well-established technology for biogas production and used for treating agricultural wastes, domestic wastewaters, and manure [163]. In Puerto Rico, using manure and residues from local dairy farms has motivated interest in using small-scale AD technologies [164].

Noteworthy is that waste streams from other sources such as elephant grass, lemongrass, pig manure, poultry droppings, sugarcane leaves, bagasse, and banana leaves present a significant feedstock potential throughout the sub-region [165]. Not just for small-scale projects but also the practical implementation of large-scale OWtE technologies given their volumes.

In the case of Central America, farms commonly produce biogas from manure, and these small-scale biogas plants can range in size between 12 and 100 cubic meters (m^3) [83]. Their upfront cost varies from US$ 675.00 to US$ 4,000.00 per plant, which means production costs ranging from US$ 40.00 to US$ 57.00 per m^3 of biogas [83]. Hence, the economy of scale plays an important role even in small-scale technologies regarding production costs. The larger a plant is, the lower its production costs are. Besides the numerous Taiwanese-model digesters installed in Central America, research centers have developed in various areas of biogas production, such as co-digestion experiments [166][167][168][169][170], especially in Costa Rica. In Mexico, the International Institute of Renewable Source (IRRI-México) initiated in 2012 a biogas program in the country, which installed around 265 biodigesters in the state of Yucatán. This program beneficiated more than 2,000 people [77].

In South America, diverse research and projects have helped adapt low-cost tubular digesters to Andean countries during the last years [149]. They were adapted to work at 3,000-4,000 meters above sea level, where extreme weather conditions and temperature fluctuations prevail [171,172]. International

[4] In April 2012, the Normative Resolution No. 482/2012, issued by ANEEL, came into force and established the initial rules for the development of electricity distributed generation in Brazil.

organizations such as the Netherlands Development Organization and the Dutch International Humanist Institute for Cooperation with Developing Countries developed national programs to create national markets for biodigesters to further diffusion/adoption of household digesters in Bolivia and Peru so-called "*Programa Nacional de Biodigestores*" [152]. In addition, there are also some non-governmental organizations (NGOs) in Peru carrying out integrated projects covering segregated MSW collection and treatment in small waste treatment plants [153]. From 2006 to 2011, pilot research and development cooperation projects have allowed the implementation of more than 30 digesters in rural Andean communities [171]. Also, in Chile, their biodigesters are applied for households to treat wastes of domestic animals [154].

3.3.2.3 Large-scale digesters

Unlike small-scale digesters, large-scale anaerobic digesters have not been widely implemented in the region mainly due to their high investment costs, technical complexity, high maintenance, among other reasons [77]. However, countries like Argentina, Brazil, Chile, and Mexico have implemented various large-scale ADs based on CSTR, UASB, and cover lagoons.

According to Cutz *et al.* (2016) [83], in Central America, the annual theoretical biogas potential of biomass-based feedstock in the region is 1,817 Mm^3/year [83]. If this theoretical potential is used in CHP applications, the region could produce 373 MW of electricity and 746 MW of heat [83]. On the one hand, even when decision-makers acknowledge the theoretical biogas potential, production has not been adequately exploited in the sub-region. On the other hand, researchers have achieved considerable advances. For example, in Nicaragua, the potential of implementing full-scale digesters was found economically viable when combining anaerobic digestion with ethanol fermentation for coffee wastes. Using fermentation by-products (i.e., wash and yeast) acquired during ethanol fermentation as feedstock for the anaerobic digester [173]. There is also an AD plant at the University of Costa Rica, generating biogas from crop residues, animal manure, and food wastes [83].

In the case of the Caribbean, there is currently a large-scale plant under construction in Puerto Rico to treat urban waste mixed with Napier grass feedstock. This plant will have a power capacity of 2 MW [174].

In Argentina, biogas technologies have been reasonably well implemented for over 20 years [156], with a list of 105 digesters in 16 provinces of various sizes and technology levels. These plants belong to the public and private sectors, production cooperatives, and NGOs [175]. A small portion of them produces energy from several plants belonging to municipalities present operational and management problems [176].

Today around 74 large-scale biodigesters exist to treat residues from the meat industry (mostly from pig farming), dairy waste, and wastewaters in Chile. Some of the notable cases are the treatment plant "La Farfana" in Santiago, which produces around 24 Mm^3 of biogas annually; the plants "Santa Irene" y "Las Pampas", with a combined installed capacity of 800 kW and supplying electricity for approximately 2,500 families [154]. Chamy and Vivanco (2007) [177] estimate biogas presents a power generation potential of around 3.5% of the installed capacity of Chile.

Colombia is one of the greatest producers of vegetable oils globally, from oil palm, soybean, colza, and sunflower. Palm oil mills are characterized by the availability of considerable amounts of by-products of high-energy such as empty fruit bunches, fibers, and shells, and palm oil mill effluent, which is particularly contaminating and a potential biogas source [178]. A study by Arrieta *et al.* (2007) [178] demonstrates the vast potential for increasing the power efficiency of palm oil mills, mainly by the use of these by-products in cogeneration plants; by generating biogas from the anaerobic treatment of wastewater and its conversion into electricity with CHP systems. Nevertheless, Ramirez-Contreras et al. (2020) argue that few mills carry out biogas capture, and only some generate electricity from biogas [179].

In Mexico, in the last decade, some programs have emerged to provide financial and technical support for implementing AD systems. Mainly through the state agency SAGARPA (Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food), now SADER (Secretariat of Agriculture and Rural Development), which has supported several agribusinesses to install AD units (primarily anaerobic lagoons) [48]. However, this has been limited to treat mainly manure for electricity generation. Rios and Kaltschmitt (2016) [49] suggest that biogas production from other organic residues should be carried out to produce energy over the following decades. In this context, in May 2017, an AD plant was inaugurated in México City (Milpa Alta) for the treatment of cactus and vegetable waste, generating almost 106 m^3 per day of biogas [51][180]. Since late 2016, the city of Culiacan installed the first large-scale DAD plant for treating 4,500 tonnes per year of agricultural residues. The plant has an installed capacity of 100 kW [47]. Another project is the AD plant in Atlacomulco, which co-digests OFMSW and wastewater [180]. Other studies have obtained favorable results using “nejayote”, which is the primary by-product of the nixtamalization [52], banana peel [53], and vinasse from tequila production [54].

In other countries, such as Uruguay and Paraguay, the potential of full-scale AD plants is gaining attention. Moreda (2016) [181] mentioned that forest and agricultural residues in Uruguay are better treated in a centralized facility receiving waste from other sources to generate electricity and digestate. Currently, there are two projects in Uruguay in which generate energy from biogas [156]. Despite presenting an adequate regulatory framework for biogas deployment, there are still few planned large-scale projects in Uruguay [156]. Moreda (2016) also estimates biogas' local potential to be between 52 and 84 Mm^3 per year, equivalent to 1.3– 2.1% of the country's total primary energy [182].

In Ecuador, in the “Social Urban Metabolism Strategies” for cities implemented in Quito, biogas technologies were the optimal technology for converting OFMSW into electricity [183]. Besides electricity, biogas production presents other essential services such as heat and biofertilizer [184] [183]. However, these technologies are not yet in place.

Biogas production in Brazil has been increasing, but its contribution to its energy matrix is still marginal (e.g., almost 0.1%) despite Brazil’s significant biogas potential [185]. The Brazilian Biogas Association (ABiogas) estimates that biogas can supply around 40% of Brazil’s electricity demand or replace 70% of its diesel consumption [158]. Hence, biogas has a pivotal role in guaranteeing energy security.

Brazil could generate approximately 43 billion cubic meters of biomethane per year, according to ABiogas 2020 [158]. If translated into energy equivalence, this amount of biogas could supply one-third of the country's electricity demand and decarbonize the national energy matrix even more, especially during peak demand. Biogas is a clean and renewable biofuel distributed throughout the national territory, in three sectors of significant investment and public policy attraction: sanitation with 7 % of the biogas potential, agriculture with 44 %, and sucroenergetic industry with 49 % [158].

Large-scale projects are based in vinasse from sugarcane mills, with two plants, and landfills, with 38 WtE plants. There are 14 WtE plants using sewage to produce energy – mostly thermal and electricity – but only one plant producing biogas as vehicle fuel in Franca, São Paulo State. The plant treats an average of 500 liters of sewage per second and produces around 2,500 Nm^3 of biogas per day, enough to replace 1,500 liters of standard gasoline daily [158][186] [187] [156][30].

The development of biogas in Brazil can avoid CO_2 emissions, up to 19.8 $MtCO_{2eq}$ per year, approximately 5% of the National emissions [30]. At the same time, several other studies have been carried out in the country to test the potential of anaerobic digestion from various sources [31][32][33][188]. In addition, several more studies specifically on vinasse from the sugar and ethanol industrial sector have found out that biogas produced from vinasse through AD technologies has excellent energy potential for large scale projects in the short- and medium-terms [148] [35] [36] [38] [37] [39] [44] [41] [43]. In addition, these studies benefit other sectors such as vinasse from corn-based ethanol plants and wastewater from cassava mills [42].

In 2016, the Brazilian government launched an auction call aimed at contracting electricity for new generation projects. The winning project was the first commercial-scale biogas plant globally using by-products of sugarcane (e.g., filter cake and vinasse) as raw material for biogas production. The project is in the northwestern region of the São Paulo State, famous for its sugar and ethanol production in the country. The biogas plant operates in 2021 and focuses on electricity generation, with an installed capacity of 21 MW [45]. Another important region for sugar and ethanol production is the western region of São Paulo, where a new commercial-scale biogas plant aims to generate electricity (i.e., installed capacity of 5 MW) and biomethane (i.e., 67,000 m^3/day). This bioenergy production can replace about 17 million liters of diesel per year [46]. The plant entered operation in December 2020, and a pipeline distributes biomethane through two cities, Pirapozinho and Presidente Prudente. Around 230 thousand people in these cities will benefit from this project through their local gas grid. Another important feature of this project is the commercial destination to nearby chemical plants of the CO_2 captured during the fermentation process in the ethanol production and during the biogas upgrading process.

Regarding DAD technology, Brazil has only one pilot project located in Rio de Janeiro State, a joint project between the company "*Methanum Resíduo e Energia*" and the UFMG. The project developed a dry anaerobic digester to treat between 20 to 30 tonnes per day of OFMSW, an initial installed capacity of 35 kW and a potential 100 kW, and designed to scale up in the future. This national technology denominated "sequential batch methanization tunnels" is adequate to the particular conditions of Brazil [189] [73].

As for biogas production based on DAD, and considering the successful experiences in Europe, these technologies have lately attracted the attention of some LAC countries, in particular Mexico and Brazil. However, there are still some structural characteristics in the region that inhibit its implementation. For example, the lack of waste sorting systems (e.g., selective collection) that generate large volumes of unsorted waste with mixtures of un-degradable materials is one of these barriers to disseminating DAD technologies in the region [189].

3.3.2.4 Co-digestion & Biochemical Methane Potential

Research in the region has also shown the importance of co-digestion to improve the performance of digestion processes. For example, Alvarez and Lidén (2008) [190] found that mixing residues such as quinoa stalk residues, “totora” (*Schoenoplectus californicus),* and aquatic flora from Lake Titicaca, with manure from llama, cow, and sheep improved the biogas generation in Bolivia. The use of totora resulted in a considerable increase of up to 130% in methane yields. Research by Santibañez et al. (2011) [191] estimates the potential of residual glycerol from biodiesel as feedstock for anaerobic co-digestion processes around 10%, 1 liter of residual glycerol for every 10 liters of biodiesel produced.

In Argentina, co-digestion of poultry manure with vegetable and fruit waste was tested in a CSTR at a bench scale. The research outcome shows that the presence of food waste improved the biogas and methane yield by more than 31% and increased not only the C/N ratio but also the dilution of nitrogen compounds [192].

In Brazil, the first large-scale co-digestion plant is in Paraná State. The plant produces biogas from 600 m^3 of sewage sludge and 150 tonnes of OFMSW per day. The installed capacity is 2.8 MW, enough to supply electricity to 2,100 households or 8,400 people [193]. Unfortunately, the plant is currently not in operation and undergoing maintenance due to operational problems with the digesters.

In Colombia, co-digestion of a mixture of cocoa industry residues, pig manure, and OFMSW resulted in high methane production (2,485.91 mL CH_4/gVS), according to the experiments developed by Rodríguez *et al.* (2017) [194]. In addition, Martínez-Ruano et al. (2019) analyzed the effect of co-digestion of milk-whey and potato stem on heat and power generation using biogas as an energy vector. They concluded that the process might be feasible [195]. However, Garfi et al. (2011) [149] has demonstrated that co-digestion does not always promote higher biogas production rates. For example, in their experiment conducted in Peru, co-digestion of guinea pig manure and cow manure did not improve biogas yields [149].

Several other works [196][197] confirm the importance of Biochemical Methane Potential (BMP) test for the evaluation and selection of residues to be treated via Anaerobic Digestion; however, as stated by Cárdenas Cleves *et al.* (2016) [198], it is a priority to define a standardized methodology to measure BMP in the region. This would increase the reliability and reproducibility of experiments.

3.3.2.5 Fermentation

Fermentation is the process by which organic material is converted into alcohol, gas, or acids (e.g., bioethanol, lactic acid, among) in the absence of oxygen and based on selective cultures of anaerobic microorganisms. Fermentation industries that produce biofuels (e.g., bioethanol) have recently shown continuous growth in various countries in the American continent [199]. The growth is based on the fact that the LAC region can increase this share and become one of the significant global bioenergy producers

[200]. However, Argentina, Brazil, and Colombia are the only countries in the region with established biofuel markets [201]. Bioethanol, for example, is Brazil´s one of the most prominent biofuels [202].

Furthermore, various other countries in the region have shown interest or have already implemented, to less extent, projects on the production of biofuels [202]. For example, in Uruguay, the goal of incorporating 5% of liquid biofuels into gasoline was recently achieved in 2016 [182]. In Ecuador, a recent governmental mandate has fostered a bioethanol production of 80 million liters [203].

Contrastingly, even when first-generation biofuel (1G) production represents a viable and convenient alternative for the substitution of fossil fuels in the region, there are recent concerns related to their economic, social, and environmental viability as energy sources [204][205]. The more preeminent problem is that biofuel production compromises food security by using arable and fertile lands. Hence, the efficient utilization of agricultural residues as raw material for 2G biofuels is becoming increasingly important to minimize socio-environmental impacts and increase economic profitability [206][207].

3.3.2.5.1 2G Bioethanol

Bioethanol production from waste materials is still undeveloped in the Caribbean Islands [82][208]. In the rest of the islands, these technologies are practically non-existent at industrial scales [82]. In Belize, the Organization of American States (OAS) has executed an assessment to identify waste streams within the forestry, agricultural, and waste management sectors to evaluate their potential as feedstock for 2G bioethanol production. The results envisioned a considerable potential for a cellulosic ethanol market [209].

LAC is the region with the most production of coffee worldwide, with Colombia and Brazil being the leading producers [210]. These are potential biofuel candidates due to their high cellulose and hemicellulose content [211] [212].

The region generates large amounts of banana residues (skin, stalks, and steams), being Brazil, Ecuador, Costa Rica, México, and Colombia, some of the largest producers of this fruit. There is a significant potential of using these residues as a bioenergy source to produce 2G bioethanol in the region [211][213][214][215][216]. However, Rambo *et al.* [211] declared that these residues are unsuitable for biofuel production due to the high moisture content that prevents transportation. Velásquez-Arredondo *et al.* (2010) [213] confirm the need for further research on variables affecting the process performance, such as temperature, reaction time, the water used in hydrolysis before discarding these residues for 2G bioethanol production.

Currently, large amounts of sugarcane bagasse result when the juice is separated from the fiber in 1G bioethanol plants. This bagasse is usually burnt in low-efficient cogeneration systems to produce steam and electricity for LAC plants. This production generates surplus electricity to be sold, thus improving the revenues of the enterprises. Diverse studies [214][217][218][219][220][221] have concluded that 2G bioethanol can compete with 1G production in LAC only if low-cost enzymes become commercially available. Wang et al. (2014) [221] state that the 1G + 2G bioethanol pathway remains less favorable economically than business as usual because current technical and economic conditions of sugar mills in LAC are more favorable to use sugarcane bagasse and trash for generating electricity via combustion.

In Brazil, two plants evidence viable production of cellulosic bioethanol from sugarcane bagasse and straw. They are: GranBio power plant installed in São Miguel dos Campos, Alagoas, and Costa Pinto Plant, from Raízen, in Piracicaba, São Paulo. However, only Raízen is already successfully producing 2G bioethanol on a commercial scale [222].

There are also expanding research efforts in Mexico to use bagasse residues from the tequila industry for the production of biofuels, at the same time propitiating their correct disposal [223][224][225].

3.3.2.5.2 Biohydrogen and biomethanol

Another alternative technique that seems attractive for the proper treatment of organic wastes and clean energy generation in the region is biohydrogen (H_2) production via dark fermentation. Various studies demonstrated the fermentation of agricultural wastes as an attractive and feasible technique to generate biohydrogen. Through the adequate fermentative conditions H_2 is obtained through the digestion of organic matter. Dry matter content of substrate (i.e., total solids) and pH are crucial variables in solid substrate hydrogenogenic fermentation of organic wastes [226].

As pointed out by Capson-Tojo (2016) [227] organic residues such as food waste have a great potential for biohydrogen production. In the case of Latin America and Caribbean, for example in Mexico, H_2 production was analyzed in batch fermentation of a substrate that consisted of a mixture of sugarcane bagasse, pineapple peelings, and sewage sludge [228]. In Ecuador, Posso et al. (2017) proposed using the H_2 derived from the OFMSW as an energy source for transportation [229]. Also, in Brazil biohydrogen utilization is gaining inertia, for example in Ceará State, there is also the Plan to produce this biofuel from biomass resources [230].

As to produce biomethanol from organic residues in the region, CO_2 is an inevitable residue from fermentation processes. Recently, there has been some attention to the option of hydrogenating CO_2 into biomethanol. In Brazil, this option is attractive and relatively easy to implement in the short-to-medium terms in pilot plants [231]. However, the low reactivity of CO_2 remains a challenge to overcome to achieve commercial deployment [231].

3.3.2.6 Landfilling with gas capture

In LAC, most solid waste goes to landfills and dumpsites. 83% of the total waste produced in the region in 2011 was collected and disposed of [232]. Landfilling is the standard practice for disposal in the region due to its low-cost management technique. In addition, it is a well-established disposal method and presents fairly structured building guidelines which are easier to be applied by municipalities when compared to other management alternatives [233]. Nevertheless, many of them are poorly located and improperly managed [234].

Until 2011, more than 99 landfills projects adopted WtE techniques; carbon markets associated with the Clean Development Mechanism (CDM) in the region [232] approved and financed these projects, resulting in the reduction of more than 19 million tonnes of CO_{2eq} from 2007 to 2012 [235]. Brazil and Mexico are amongst the top five countries worldwide that receive more income from mitigation projects. Most of the Certified Emissions Reductions (CERs) resulted from biogas capture projects in landfills [92].

Regarding the Caribbean Islands, there are some successful cases and proposals. A landfill with gas capture infrastructure in the US Virgin Islands supplies biogas to an electricity generation plant. The plant has an installed capacity of 815 kW and supplies electricity to around 900 households on the island [236]. Other countries like the Bahamas, St. Lucia [237], St. Vincent and the Grenadines [238], and Grenada [239] have also demonstrated interest in implementing landfill gas capture projects. Implementing efficient technologies for waste treatment and volume reduction is becoming increasingly important in these islands, considering the lack of locations for solid waste disposal and the pollution caused by traditional disposal methods, which affects the tourism sector [82].

In Mexico, the city of Monterrey successfully implemented the first landfill gas capture project in 1990, and other municipalities have replicated this model. Nowadays, landfills with gas capture infrastructure in Mexico receive more than 19 million tonnes of waste annually, amounting to an installed capacity of 16 MW. The biogas from waste gets converted to electricity that moves subways and provides safer streets through public lighting. At the same time, these projects cut down municipalities' operating costs and reduced GHG emissions [232].

Other cities in LAC have also installed similar systems. For example, in Uruguay, the city of Maldonado uses the biogas captured from landfills to run a plant with an installed capacity of 550 kW [232]. The economy of scale is an essential factor for municipalities. The Uruguayan Ministry of Environment detected that gas capture technologies are a heavy financial burden for small populations. Hence, cities with over 100,000 inhabitants seem to be the most appropriate for implementing gas capture systems [232]. In Chile, a significant share of biogas produced comes from landfills [154][240]. In Colombia, the landfill of "Doña Juana" runs a biogas-based power plant with an installed capacity of 1,7 MW. Another power plant is under construction in the landfill of Guayabal, located in Cucuta, Colombia. The project is estimated to supply electricity for 25,000 people.

In the case of Brazil, the use of biogas from landfills is well implemented for electricity production and increasing. Currently, there are thirty-nine projects in operation in the country. In São Paulo, there are nine landfills where biogas produce electricity [100]. The first experience in the region used landfill biogas as fuel gas for the urban bus fleet in Campinas [241] [242]. Since January 2015, government officials have regulated the use of biomethane obtained from landfills [243]. The National Agency for Petroleum, Natural Gas and Biofuels (ANP) must authorize any Biomethane production plants to enter in operation under the Resolution No. 734 (Brazil, 2018). Biogas and biomethane are expected to play a significant role in the country's energy matrix [244]. In Brazil there are three sanitary landfills that produce biomethane: In the State of Ceará the Gas Company CEGAS, already injects 15% of biomethane from landfill biogas in its commercialized natural gas system [245]. The other two are located in Rio de Janeiro: The Gás Verde in the Seropédica landfill & Dois Arcos in São Pedro da Aldeia. These plants carry out the biomethane distribution by beam trucks [246].

Landfilling is still seen as a viable option for waste disposal because of its low operation costs, mainly because the land is not an issue for its implementation. However, in some cases, available lands close to urban centers are every time more scarce which results in large transportation distances. Also, there is an ongoing debate on whether landfilling should prevail compared to other thermal and biochemical treatment technologies [100]. Additionally, uncontrolled biogas losses in landfills must also be considered, which could reach up to more than the halve of the total biogas production. This might be an environmental disadvantage of landfill biodigesters. Thus, in the long run, environmentally sound management options can potentially replace landfilling practices in Brazil [247].

In line with this, some countries in LAC are already closing their dumpsites; for example, in Buenos Aires, an open-air dumpsite occupying an area of 8 hectares for 20 years was recently closed [248]. In Brazil, the dumpsite in Brasilia, which served between 4 to 5 million people, has been partially closed, and MSW is now diverted to a new sanitary landfill. The city is also currently building some sorting and recycling plants, where urban waste can be sorted appropriately and treated [249]. In 2011, Mexico closed its largest open-air dumpsite [250]. Hence, even when several studies and projects in LAC have demonstrated the benefits of MSW landfilling with gas capturing in the region, just in the last decade, there have been some perception changes towards implementing thermochemical or anaerobic digestion. These mindset changes have resulted from technical and environmental advantages of being more efficient energy recovery options.

3.3.2.7 Microbial fuel cell

In the LAC countries, the development of Microbial fuel cell (MFC) projects is at the research level. Some studies highlight their potential in the region, especially in the Caribbean context [251]. In Mexico, another study [252] concluded that the application of MFC for municipal wastewaters and landfill leachate is promising for effluent depuration and bioenergy generation. In Brazil, Rachinski et al. (2010) [253] describe MFC as a promising technology for electricity and fertilizer production based on animal and vegetable solid wastes and as an alternative to waste remediation.

3.4 General challenges and opportunities

3.4.1 Challenges

In general, according to our literature review, the identified challenges the LAC region is facing for an adequate implementation of OWtE technologies are classified mainly as institutional, financial, technical, and educational, as hereafter mentioned:

- Dearth or ineffectiveness of waste management strategies, which require the balancing of optimized waste reduction practices, recycling, recovery, and landfilling [209] [82], together with educational and technical programs;

- Lack or deficient institutional frameworks, environmental legislation [128], and business models [30].
- Need for fostering new markets for biogas and creating public incentive policies for technology implementation [254].
- High technology costs for the equipment and maintenance.
- Low or no financial incentives to facilitate energy generation from wastes and the implementation of modern waste management strategies [209];
- Lack of reliable and relevant information on urban waste (i.e., amount of waste, waste composition, and potential uses of collected waste), or agricultural residues (i.e., quantities, types, BMP´s, among other characteristics) according to the situation in each country [209];
- In many countries of the region, there is a dearth of engineering companies, manufacturing equipment, and a prevailing low state of technology that has limited the region´s capacity to implement OWtE [83].
- Other significant problems in the region are the absence or limited know-how, capabilities, and expertise on the existing technologies [82]; furthermore, research and development for new and appropriated technologies.
- Lack of research to prove the competitiveness of bioenergy production as compared to fossil fuels [128]; and
- Low prices of fossil fuels are slowing the development of renewables in LAC. Hence waste-to-energy alternatives may become less attractive throughout the region.

In LAC, one of the main challenges identified and pointed out by various authors [121][112] [185] is to find the economic feasibility of the projects, considering the high technology, production, and maintenance costs involved. The costs from generating biofuels or biogas in the region from residues are generally higher than the fossil fuels resources tariff currently in the market [30]. The development of technologies that are economically feasible for the region is transcendental for OWtE to thrive.

Considering that OWtE systems represent a part of an integrated waste management strategy and are not always the most sustainable solution, experts should carry out a detailed analysis to evaluate which technology might be more suitable. Further research is also required to properly seek the contributions these technologies can provide to reduce emissions and the viability of implementing and diffusing WtE technologies to promote sustainable energy systems in the region.

3.4.2 Opportunities

The environmental, technical, and economic opportunities and benefits of these treatment methods have enhanced the utilization of organic waste to produce energy in LAC. Diverse research and projects have demonstrated the plenty of advantages that come with this. The opportunities have lately expanded and arisen interest throughout the region due to all these benefits.

3.4.2.1 Environmental opportunities

- The implementation of these technologies could contribute to face the multiple problems derived from the disposal of solid waste in sanitary landfills and dumpsites [255], e.g. reducing the uncontrolled methane emissions and generally untreated lixiviates in landfills;
- Accordingly, the countries in the region could also benefit from OWtE technologies to reduce GHG emissions and attain national goals established by the NDCs under the new international agreement adopted in December 2015 in Paris [2].
- For some OWtE technologies, manly anaerobic digestion, the resulting digestate materials as fertilizer, and soil improver contribute to ‘close the loop’ of the substrates lifecycles and circular economies [256].

3.4.2.2 Social opportunities

- Beyond improving the sustainability of each country, the production of bioenergy with waste also helps to enhance energy security, diversify their national energy mix and reduce diesel fuel imports [229].
- Harnessing the potential from residual biomass would also enhance the development and wellbeing of the rural and urban communities, not affecting their food security [215], and further bringing much-needed employment in the rural areas.
- Public health is also beneficiated, reducing pollutants in the environment with significant gains in better sanitation systems reducing poverty and illnesses. Also, the use of biogas as vehicle fuel can reduce air pollution (e.g., particulate matter) in cities; however, attention must be paid towards undesired emissions of methane and nitrous oxide [257].
- Job creation, personnel training and strengthening local communities

3.4.2.3 Economic opportunities

- Increase the revenues generated by the utilization of residues or by-products that large enterprises usually discard;
- The economical use of residual biomass in rural areas could generate extra income for small farmers and enhance their development. [215].
- Create new alliances between engineering companies or firms and academic units, allowing for mutual improvement and gaining technical experiences regarding new technologies [83].

3.5 Summary

In LAC, every year, large amounts of agricultural forest and urban solid residues are generated. This research has identified their advantages and challenges as alternative energy sources through biochemical and thermochemical processes. In recent years, various small and large-scale projects have occurred. Several studies have presented technical, environmental, and economic analyses of different technologies in the region and their comparative performances for bioenergy production.

3.5.1 Thermochemical

Incineration is the thermochemical technology most commonly practiced in LAC [82][83], demonstrating further potential. Nevertheless, there is an ongoing debate on whether this is the proper organic waste treatment method, considering the environmental drawbacks and low process efficiency these technologies portray. Gasification and pyrolysis present some advantages over combustion, such as being more thermally efficient, utilization of downstream products (biofuels, chemical or fertilizers), and higher and cleaner bioenergy production, among others [85].

Key findings:

- Research and development have widely applied combustion technologies in LAC for agricultural and forest residues to produce electricity, considering it is still the least costly thermochemical option [94]. Sugarcane bagasse and straw are the primary combusted residues [83].
- Diverse densification techniques have been applied in the region, such as pelletizing, briquetting, and torrefaction. These intend to achieve adequate properties and higher calorific values. Today, Argentina, Brazil, Chile, Costa Rica, Honduras, Mexico, and Uruguay [105] produce pellets at the industrial level for national bioenergy markets. LAC accounts for a considerable potential to palletize and export agricultural and wood residues.
- Diverse experimentation indicates that gasification has ideal characteristics for producing energy in LAC. Countries like Cuba [83] and Brazil have implemented gasification systems [128], which are valuable experiences for further transfer of technologies.
- Even when pyrolysis is the minor thermochemical technology practiced in the region [82][83], various researchers have demonstrated it as an efficient technology to treat OW and produce renewable fuels in the region. However, in Central America, for example, pyrolysis is deduced to be the least preferable technology [83]. Further studies are necessary to understand more on the economics and logistics of the process [109].

3.5.2 Biochemical

Biochemical technologies comprehend anaerobic digestion, fermentation, landfilling gas capture, and Microbial fuel cell (MFC) technologies. In recent years, R&D on the biochemical treatment of organic residues in LAC has focused on small-scale AD [1] and landfilling; and fermentation to less extent. Notwithstanding, interest in large-scale biodigesters, second-generation biofuels, and MFC´s has been gaining ground in the last years, with some countries in LAC already implementing such projects.

Key findings:

- Diverse stakeholders have successfully implemented low-cost household biodigesters in rural zones throughout LAC. They have proven it as an appropriate technology to treat agricultural residues, produce fertilizers and energy. However, according to Garfí *et al.* 2016 [84], there are still several barriers to overcome to improve and further disseminate the technology; such as lack of awareness of the existence of these technologies or low operation and maintenance, among others.
- Large-scale AD has not been widely implemented in the region due to its high investment costs, technical complexity, and high maintenance demands [77]. However, Argentina, Brazil, Chile and Mexico have implemented more than a dozen CSTR, UASB, and cover lagoons for the treatment of sewage waters and industrial and agricultural residues. Other countries have similar experiences to less extent. Full-scale dry AD has been implemented in Brazil and Mexico.
- Significant research in the region has evaluated the benefits of co-digestion to improve the performances of biodigestion processes. BMP test have also been implemented throughout the region.
- Currently, the fermentation industries that produce 1G biofuels have shown continuous growth in various countries in LAC. Only Argentina, Brazil, and Colombia have established biofuel markets.
- The inclusion of 2G biorefinery is lately gaining ground in LAC. R&D is developing on the potential of residues from diverse crops such as sugarcane, coffee, corn, banana, palm oil, and rice. However, the application of such projects has some challenges, such as technology readiness or profit-earning capacity. Two treatment plants: GranBio and Raízen, have shown optimistic projections on 2G paths in Brazil. Raízen produces bioethanol from sugarcane bagasse and straw.
- Biohydrogen production via dark fermentation is gaining attention in the region, with proposals to use the OFMSW and other residues as feedstock.
- In LAC, 83% of the total waste produced in the region was destined to landfills and dumps in 2011. More than 99 WtE landfills projects were approved and financed in the region by the CDM [232]. Brazil and Mexico are among the five countries worldwide that receive more carbon incomes.
- Some countries in LAC are already closing their dumpsites. For example, Buenos Aires, Brasilia, and Mexico City. These cities are changing towards the implementation of thermochemical or AD, given their technical and environmental advantages.
- MFC technology in LAC is at the research level, with some studies highlighting their potential.

Currently, there is an ongoing debate on an adequate technique to treat organic residues because of their energy potential. In recent years, diverse entities have implemented various small and large-scale OWtE projects, and several studies have presented environmental and technical analyses of different OWtE technologies in LAC. Throughout this literature review, through this research, it was found out that OWtE technologies are not always a good option, and the benefits of keeping agricultural residues on the fields cannot be neglected.

The feasibility of implementing one technology over the other for each residue is not set in stone but rather depends on each country's conditions and mainly on market and technological factors. Therefore, there is a need for genuine analyses and studies for each unique case. The review of these technologies' state of the art resulted in anaerobic digestion and gasification being deemed the two most promising technologies, given the technical and environmental advantages they offer.

Furthermore, the implementation of OWtE technologies is crucial for the sustainable development of LAC and significantly contributes to improving waste and energy systems and several social and economic benefits. Further works shall determine the bioenergy production potential for the diverse organic residues and demonstrate the applicability of small and large-scale OWtE treatment plants throughout the Latin-American and Caribbean region.

Table 3: Summary of the content analysis and its coded references

COUNTRY OR SUBREGION		OWtE TECHNOLOGIES						
		COMBUSTION	GASIFICATION	PYROLYSIS	ANAEROBIC DIGESTION	FERMENTATION	LANDFILLING GAS CAPTURE	MFC
CARIBBEAN	**Caribbean**	[82]	[82]	[82]	[82] [160][160]	[82] [209]	[82] [234] [237] [239]	[251]
	Anguilla			[135]				
	Aruba		[115]					
	Barbados		[116]		[160]			
	The Bahamas						[237]	
	The British Virgin Islands	[82]						
	Dominican Republic	[111]						
	Cuba	[88]	[88] [117] [118]		[151]			
	Grenada						[239]	
	Haiti			[133]	[162][163]			
	Jamaica			[134]		[208]		
	Puerto Rico				[164] [174]			
	Santa Lucia						[237]	
	Saint Kitts and Nevis			[136]				
	Vincent & Grenadines						[238]	
	US Virgin Islands						[236]	
CENTRAL AMERICA	**Belize**				[161]	[209]		
	Central America	[83]	[83][119]	[83]	[83]	[83] [87]	[87] [90]	
	Costa Rica	[98] [108]			[150][151] [166] [167] [168] [169] [170]			
	El Salvador		[83]					
	Guatemala	[90]						
	Honduras	[90]			[151][197]			
	Mexico	[86][92][102][111] [122]	[86] [122]	[86] [137]	[77][4][151][48] [49] [47] [51][52] [53] [54]	[92] [223] [224] [225] [228]	[247] [250]	[252]
	Nicaragua	[91]			[151][173]			
	Panama		[83]					
SOUTH AMERICA	**South America**					[205]		
	Argentina				[156] [175] [176][192]	[207]	[248]	
	Bolivia				[147] [152] [172] [190]			
	Brazil	[93] [94] [96] [99] [100] [101] [103] [106] [129][33]	[126][127][128][129][130]	[129] [139][140] [141] [142] [143] [144]	[93] [100] [148] [155] [156] [157][47] [186] [187] [30] [31] [32] [33][188] [35] [36] [38] [37] [37][39] [41] [43] [42] [45][46][189] [73]	[128] [211] [217] [218] [219] [220] [221] [222] [231] [254]	[93] [94] [100] [241] [242] [243] [244][245] [249]	[253]
	Chile	[107] [111] [120]	[120]		[154] [177] [191]	[205]	[240]	
	Colombia	[109][112]	[121][123] [124]	[132] [145]	[151] [178] [179] [194][195] [196] [198]	[204][213]		
	Ecuador	[125] [183]	[125]	[146]	[125] [151] [183]	[203] [200] [214] [215] [216] [229]		
	Guyana			[138]				
	Paraguay				[156] [182]			
	Peru	[110]			[149][153] [171] [184]			
	Suriname	[102]	[102]		[102]		[102]	
	Uruguay				[156] [182]			
LATIN AMERICA		[95] [105]			[77] [84][199]	[78] [199] [202] [201] [210][212]	[232]	
OTHERS		[79] [80] [81] [85] [113][114] [119] [126] [130] [146] [206] [210] [233] [235] [2]						

4 CASE STUDIES; DRY AND WET ANAEROBIC DIGESTERS TECHNICAL BENEFITS AND DISADVANTAGES

4.1 Introduction

This research conducts two case studies to determine the pros and cons of DAD and WAD technologies and to analyze their effects on Brazil's waste management, water savings, and nutrient and energy generation. The aim is to identify DAD and WAD systems' benefits and disadvantages using a multimethod research design. Additionally, the study plans to analyze how much these technologies can reduce GHG emissions based on numerical data.

This research phase focuses on developing two case studies to analyze the performance of a DAD treatment plant already constructed in Brazil and compare it with a local existing traditional WAD plant. The assessment methods are the multicriteria decision analysis (MCDA), analytic hierarchy process (AHP), and the Material Flow Analysis (MFA), which considers all mass and energy flows and compares them. This method uses an analytical framework to quantify and analyze materials and fluxes while passing through a well-defined system, delimited by a system boundary.

Thus, we searched for a WAD plant, targeting a project like the studied DAD plant, to match the systems as much as possible.

4.1.1 Case Studies

This research develops structured frameworks for the development of the case studies, including elements by Runeson & Höst (2009) [258]; and Yin (2003) [259], which results in five major process steps: (1) Case study design and setting up the objectives; (2) Case study protocol; (3) Data collection; preparation and collection of the evidence; (4) Data analysis and interpretation; and (5) Reporting.

4.1.1.1 Case studies methodology and definition

The primary purpose of these case studies is to attend the second specific objective through primary and secondary data collection methods. This objective was further refined with the following list of exploratory queries:

i. What are the benefits and disadvantages of DAD compared to traditional WAD technologies on water, waste, and energy systems?
ii. What is the GHG mitigation potential of the DAD and WAD technologies?

With the development of these case studies, this research intends to determine the environmental and energy performance of existing anaerobic digesters. One in the city of Foz do Iguaçu, called Itaipu Production Unit and in this study denominated the Anaerobic Digester 1 (AD1); and the other one in Rio de Janeiro, here referred as the TMethar treatment plant or Anaerobic Digester 2 (AD2). The purpose was to evaluate the GHG impacts of these existing solid waste management systems, focusing on the potential climate change impacts. The intention is to compare their efficiency on resource utilization and emissions. For this purpose, the delimitation of the system´s boundary shall be essential to identify the main energy and material flow limits; thus, the study identifies and quantifies the significant materials and fluxes, attempting to calculate the overall emissions and production quantities.

The units of analysis are the quantities of water, waste, and energy that these treatment plants utilize and generate. This approach allows for a direct comparison between DAD systems and traditional WAD systems. The expected results favor one technology over the other in the specific contexts of deciding how solid organic residues can be more proficiently treated. The comparison between these systems should allow to define in which specific cases DAD determinately and objectively could be preferable to WAD and vice versa.

4.1.1.2 Case studies protocol

A detailed case study protocol helps to define and support a well-structured research approach. The designed case study protocol follows an outline proposed by Maimbo & Pervan (2005) [260], as in Table 4: *Outline of the case study protocol. Source: [260]*

. See the protocol in Annex A.

Table 4: Outline of the case study protocol. Source: [260]

Section	Purpose
Preamble	It contains information about the protocol's purpose, data and document storage guidelines, and publication—a brief overview of the research project and the case research method.
Procedures	A detailed description of conducting procedures for each case ensures uniformity in the data collection process and facilitates both within and cross-case analyses.
Research instrument(s)	Mainly interviews and questionnaires to facilitate and ensure consistent data collection.
Data analysis guidelines	It is the description of the analysis procedures and schemes utilized during the analysis.
Appendix	Template letter to invite participants Questionnaires

The case study protocol intends to define a detailed procedure for the collection and analysis of the data. It serves as a guide throughout the case studies research, enhancing the validity of the information and preventing any data planned to be collected. It also helps to decide which data shall be requested, sources to use, and specific questions during the interviews or questionnaires.

4.1.1.3 Objects under investigation

4.1.1.3.1 Itaipu Production Unit CIBiogas: Wet Anaerobic digester

The Itaipu Production Unit (IPU) is located at the Itaipu Binational complex in Foz do Iguaçu, Parana, at 194 mts above sea level and warm temperate climate. Its operations began in January 2017 and were officially launched in June of the same year, becoming the first plant of its kind in Brazil. The Itaipu Production Unit, aims to treat the biomass waste from the restaurant substrates generated in the ITAIPU complex and other residues to produce biomethane for vehicle utilization. The digestate functions as biofertilizers to recuperate degraded lands. The treatment plant resulted from the collaboration of Itaipu Binational and the CIBiogas Institute. Hereafters are some of the main characteristics of this treatment plant:

Figure 6: Itaipu Production Unit. Source: CIBiogas files

Biodigesters and substrates

Substrate's content: The Itaipu´s treatment plant uses mainly organic waste from the restaurants at the Itaipu Binational area as substrates for biogas production. It also eventually processes external waste from other sources such as the Federal Police Departments and the Ministry of agriculture, livestock, and supply. These external residues are carefully evaluated and inspected by government agencies and contribute to increased biomethane production. Regularly, restaurant waste averages 250 kg, plus an average of 200 kilograms (kg) of chocolate powder (cocoa) and 100 liters (L) of soybean/corn oil daily.

Specialists carry out frequent laboratory tests to sample any new external substrates (if these are still not registered in the databases). Aside from the restaurant residues, cocoa, and soybean/corn oils, other common external substrates are beans, corn, fish, shrimp, sausages, fruits, beer, cheese, and garlic. Residues from the Federal Departments and MAPA such as corn, soybeans, and beans arrive at the unit for treatment in the degradation process, which is very different from their natural forms after harvesting these grains.

Figure 7: Restaurant wastes and grass pruning residues (previously used). Source: CIBiogas files

Transportation: Organic wastes are stored daily in plastic bags, then the waste is transported with trucks from an Itaipu's outsourced company. The distance from the restaurants to the plant is around 2 km. These existing transportation processes in the unit do not use any fossil fuels but rather the produced biomethane.

Substrates total solid content: The TS content is an average of 12%. This value is very variable, and it could be between 5 to 15%. After the waste sorting process, a crusher is lubricated with additional water and alters its TS composition.

Impurities: At the beginning of the treatment process, it is necessary to remove non-organic materials, such as plastics, metal cutlery, and other contaminants (e.g., juices, soft drinks, among others), which the plant operators currently carry out; but in general, the residues are reasonably well separated when they arrive at the treatment plant.

Structure and Monitoring of the processes: Currently, the monitored processes are:

- Biomass temperature (3 temperature sensors in bioreactors);
- Biomass level in the reactors (ultrasonic level sensor);
- Biomass pH (pH sensor);
- The organic loading rate is kept constant.
- Monitoring of physical-chemical parameters: FOS/TAC Ratio, ammonium (mg/L NH4 +), total solids, fixed solids, and volatile solids. In addition, new substrates get analyzed with BPM tests.

Monitoring: An automatic system monitor and control the entire biogas plant remotely, presented in the following image:

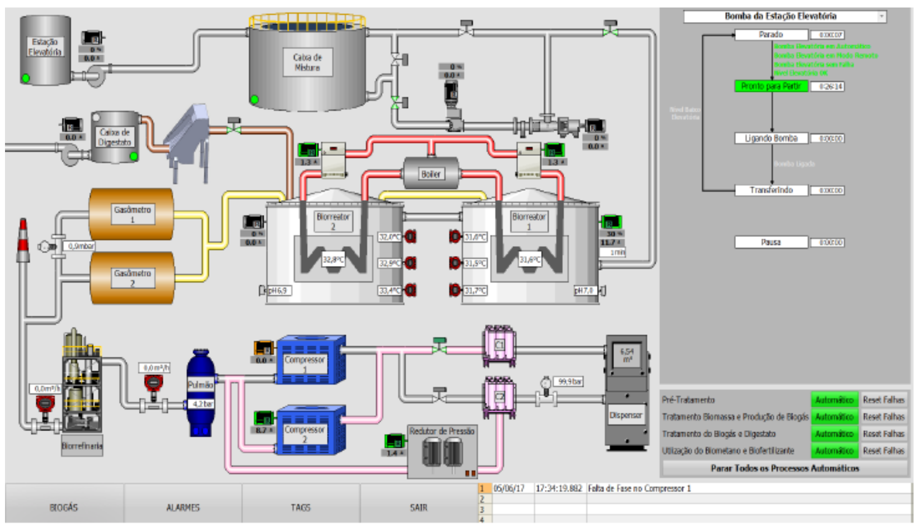

Figure 8: Automation system diagram ERNEX
Source: Presentation at the IV Forum of Biogas in São Paulo [261].

Biodigesters Structure: The digesters are conformed of light material that does not overload the base and contemplates the following:

- Modular structure to assemble and adapt;
- Impermeability;
- structural security;
- Thermal efficiency.

Figure 9: WAD Biodigesters at IPU. Source: CIBiogas files

The following image presents the elemental mass flow of the treatment system:

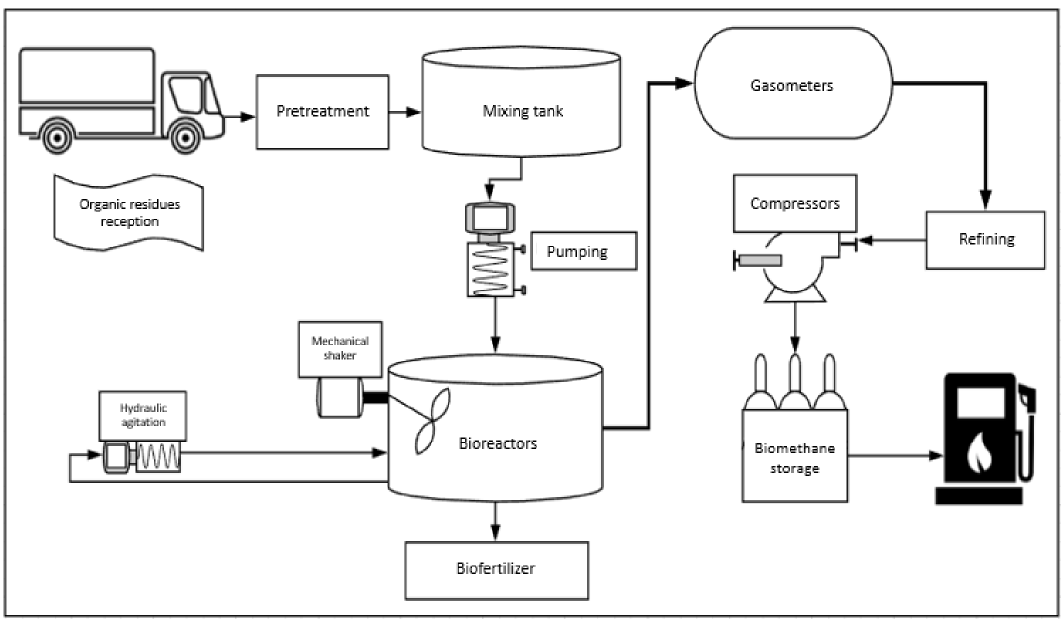

Figure 10: IPU´s mass flow of the treatment system. Source: CIBiogas files

Outputs and emissions

Digestate and biofertilizers: Currently, most of the digestate is used for recirculation. After being used in the biodigester process, effluents are transferred to another reactor for better treatment, where COD, Ammonium, and NPK are controlled. The plant performs the hydraulic recirculation of the digestate two times per week. The surplus digestate is then transformed into biofertilizers and used to fertilize Itaipu´s complex green areas.

Biogas and biomethane: Biogas undergoes refining processes to produce biofuel (biomethane) and supply Itaipu 's fleet. For the cleaning and purification of the biomethane, H_2S removal by activated carbon, CO_2 removal by water scrubbing system, and moisture removal by pressure swing adsorption. This cleaning process is carried out in a biorefinery with an operative process integrating this water scrubbing and PSA methods, a technology developed in Brazil.

The gasometers store the resulting biomethane for the necessary time to fill up the cylinders. From there on, biomethane is supplied to a fleet of more than 70 vehicles from Binational Itaipu.

Leaked or emitted gases: CO_2 emissions occur during the refining process. Also, a portion of CH_4 is lost during the CO_2 removal process. The existing processes in the plant do not use any fossil fuels.

Social Aspects

Social acceptance of the project: The plant is installed inside the Itaipu complex, in front of the plant's spillway viewpoint, causing no social impact or disturbances.

The unit frequently receives technical visits from schools, universities, and diverse companies.

Creation of job positions:
Outsourced operation - 3 operators that carry out the pretreatment activities (food waste crushing), general maintenance, and cleaning of the plant. Two men and one woman;
Operation and maintenance -two technicians (men);
Management - one manager (woman);
Project inspection - two inspectors (men).

Other social benefits:
Conduction of technical visits contributing to propagate knowledge;
Reduction of the amount of waste transported to the landfill, increasing its useful life, and taking advantage of the energy potential of the waste to produce biofuels. In addition to reducing the CH4 emission that would occur if the waste went to the landfill;
Reduction of greenhouse gas emissions with the replacement of fossil fuels;

Other aspects

Inoculum: Bovine manure serves to inoculate and initialize the reactors.

Possible improvements: Implementation of biogas flow meters, since up to date only theoretical calculations are estimated during the production of biogas. In addition, the plant could install biomass inlet and outlet flowmeters to obtain more accurate values concerning the hydraulic retention time, which is currently only estimated.

Water: The system includes water portions during the waste crushing process, but the quantity is not measured (only estimated). There is currently no water flow meter because there is very little used in the biodigestion process. Homogenization is carried out with the biomass itself (recirculation). Water only comes in particular cases or for some effect of corrective or preventive maintenance.

Machinery: The plant uses a forklift to receive the waste and position it on the crushing platform.

Future perspectives

The project´s leaders intend to grow the treatment plant and be able to treat all organic waste produced at the Binational Itaipu´s complex and additional external residues, as follows:
15 tonnes of food waste per month;
30 tonnes of grass per month;
300 m³ of sanitary sewage per month;
Reduction of 10 tonne/month of the otherwise emitted GHG;
Conditioning of more than 200 hectares of the complex´s green areas with biofertilizers;
Receive waste from the Ceasa market (Foz do Iguaçu) for new tests.

All this could be achievable with the consolidation of reliable results, which can help to provide valuable subsidies for specific investments.

Furthermore, there is also currently the intention to include a CHP system for electricity and heat generation on a demonstrative basis, but with no starting date. With the current biogas production rates, the generation capacity is around 200 kWh/day if all the biogas produced per day was used for energy generation.

4.1.1.3.2 TMethar Comlurb treatment plant; Dry anaerobic digester

The TMethar treatment plant is in the Caju neighborhood, inside the Residues Treatment Unit (UTR), in Rio de Janeiro. It is at the city company of urban cleaning facility, Comlurb, and started operations in November 2018. The treatment plant´s developers are the UFMG, in partnership with companies Methanum Tecnologia Ambiental and Comlurb. It has a processing capacity of 30 tonnes of organic waste per day, equivalent to the waste generated by 25 thousand inhabitants, and through its batch digestion system produces fertilizer and biogas. The estimated monthly biogas production capacity is enough to feed a fleet of 1,000 cars or generate energy to supply over a thousand houses. It is the equivalent of extracting 100 to 150 cubic meters of biogas per processed tonne of organic waste, with 50% to 60% methane content [262]. The TMethar is the first plant to use dry garage technology in Brazil.

In the treatment plant, the reception yard or patio with a total of 200 mts^2 receives the OFMSW. It is then transported to the modules or solid-state batch methanization (MESB) made up from reinforced concrete. These are sealed for a certain period for the anaerobic microorganisms to degrade the organic matter and produce biogas. At the same time, the fresh leachate liquids pass through a percolation system where it is treated and stabilized in the Inoculum Production Unit (InPU). The InPU also produces a certain quantity of biogas and recirculates small amounts of the leachate to the MESB system, which serves either as inoculum or for moisture correction. Biogas and digestate are treated on-site and converted into electricity (potentially thermal energy) and biofertilizers. This process generates significant environmental and economic benefits, promoting a more sustainable and decentralized sanitation system in the city.

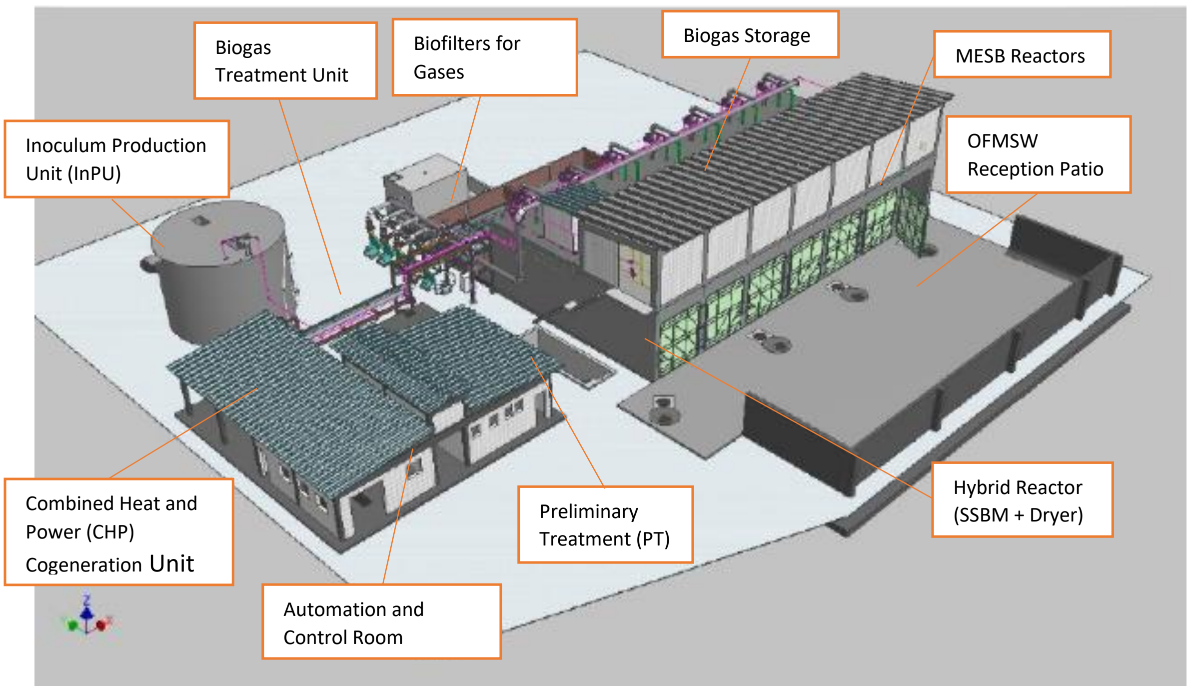

Figure 11: Image of the TMethar treatment plant. Source: [263]. *Edited by author.*

The TMethar is composed of the following central units:

i) Six MESB reactors;
ii) A hybrid reactor that can be operated either as MESB or as thermal-drying reactor;
iii) A wholly mixed anaerobic reactor for leachate stabilization and inoculum production unit InPU;
iv) A non-pressurized gasholder;
v) A biofilter to treat the waste gases.

Hereafter the research presents some of the main characteristics and processes of the treatment plant.

Substrates

Substrates content: The Waste Treatment Unit Caju (RTU-Caju) receives more than 1,500 tonnes of OFMSW per day, collected from homes and large generators, such as supply centers (e.g., CEASA), supermarket chains, restaurants and hotels, and different neighborhoods with diverse waste consumption and production patterns offering sufficient diversity to simulate the conditions of other Brazilian municipalities [264]. The plant also receives and treats residues and leftovers from the ground city pruning.

Each of the MESB reactors receives loads of organic residues that vary between 56.6 and 77.8 tonnes to be processed in batches of 30 days, achieving a total of 15.6 tonnes per day, or 468 tonnes per month. This treatment capacity corresponds to only around 1% of all OFMSW received at the RTU-Caju. In each MESB reactor, the operators form 2.5 m high piles.

Figure 12: OFMSW disposed in the residues Patio and residues from the ground city prunings.

Transportation: This relatively new biogas plant lies in Caju, which is the site where the municipal solid residues are deposited. Thus, there is a considerable reduction in transportation compared to the previous waste disposal site in the Seropédica´s landfill. With this, there is no diesel consumption accounted for this. This asset is one of the main advantages of the TMethar treatment plant.

Substrate's characteristics: The TS content is 215 kg ST/tonne of OFMSW, or an average of 21.5%. It has a biodegradation potential (VS/TS) of 0.88, which results in organic content of 190 kg SV/tonne of OFMSW. The average specific mass is 560 kg/m^3 of OFMSW.

Processes and Monitoring: The biological treatment process at TMethar divides into five integrated steps:

(i) Reception and preparation of organic waste;
(ii) Solid-state methanization via sequential batch (MESB);
(iii) Stabilized leachate recirculation via the Inoculum Production Unit (InPU);
(iv) Post-treatment of the digestate;
(v) Storage, desulfurization, and energy conversion of biogas via CHP (Figure 13).

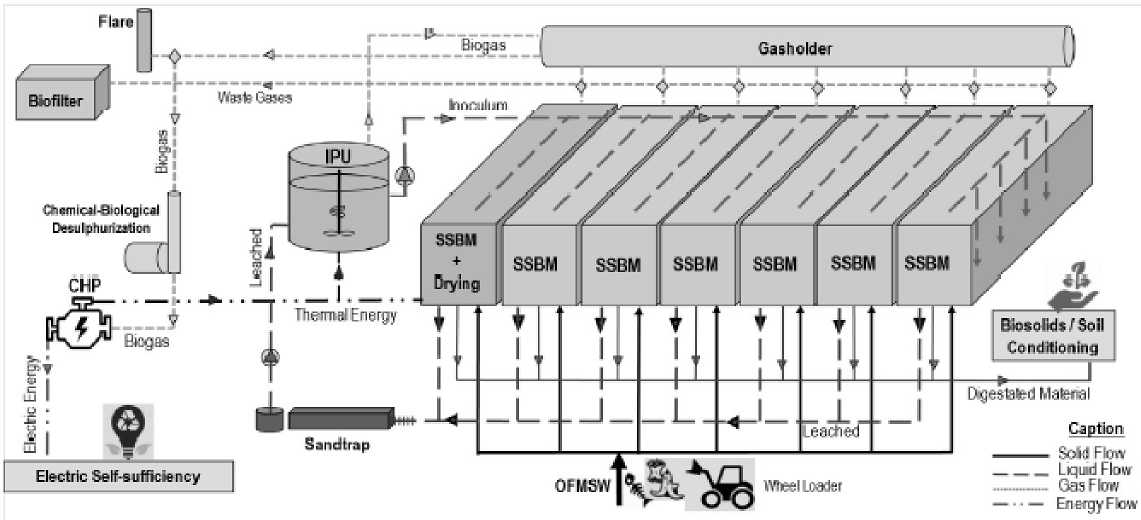

Figure 13: Flowchart of the TMethar processes Source: [264].

Biodigesters Structure: Within the biodigester, there is an aeration system that makes possible the temperature increase for the thermophilic treatment range, reaching values of up to 57°C, which allows the sanitization of the organic material. Without aeration, the temperature reaches only a maximum of 38.4°C.

Outputs and emissions

Digestate and biofertilizers: The production of biofertilizers is an important part of the treatment process. After methanization, the resulting digestate is taken to a maturation stage for its final stabilization. At the TMethar facility, this process usually happens in the MESB reactors (via controlled aeration composting) or in the external composting yard. Then the produced digestate is sieved to remove the inert materials and organic residues with a particle size greater than 10mm. The equivalent production quantities are in

Table 12.

The produced biofertilizers help recover soils and recuperate degraded lands in the city and are marketed as organic fertilizers or soil amenders, which depends on their physical-chemical and microbiological characteristics [265] in [266]. This revenue is on its way to generating an important income source to make the treatment processes economically viable.

Biogas and biomethane: At the treatment plant, currently, the produced biogas passes through a purifying and treatment process where it is first desulfurized, then sent to the CHP cogeneration unit and turned into electricity and heat. Thus, the energy available in the biogas produced is approximately 100 KW, converted into electricity. This energy is used internally to ensure the self-sufficiency of the methanization processes. On the other hand, although the treatment plant is configured to perform the thermal exploitation of biogas, this operation is currently not carried out.

Leaked or emitted gases: The disposal of the OFMSW in the Patio generates considerable volumes of leachate, which is canalized and collected by drainage devices and sent to preliminary treatment (PT) and later to the InPU system. The purpose of the PT is to remove all coarse solids and sands to avoid including any inert materials in the biological reactors.

In addition, the Eco Park-Caju itself has re-used all the liquid effluent generated by the InPU, either as biofertilizer for vegetable gardens and city gardens or the correction of moisture in the composting beds. Usually, there is a considerable volume of these liquid residues of approximately 0.18 m^3/tonne OFMSW. However, this value varies, and there are periods when there is no generation of surplus effluent.

Future perspectives

Aside from the current electricity production, there is a plan to set the treatment process for producing biomethane as vehicle fuel. The treatment plant officials estimate a production potential of 15,764 Nm^3 of biomethane per month. Ornelas-Ferreira (2020) [264] suggests that this can result in more significant economic gains and more extensive avoidance of GHG emissions than with the current electricity generation scenario.

On the other hand, the thermal energy could be utilized to dry and sanitize the digestate, improving the produced biosolids´ microbiological properties and physical-chemical characteristics, or as an internal heating system for the InPU system. Assuming a thermal efficiency of 45%, the cogeneration unit can generate 269 kW of thermal energy (installed capacity), and it is sufficient to supply 193 MWh/month of thermal energy.

(a)

(b)

Figure 14: TMethar: (a) SSMB reactors; (b) Inoculum Production Unit (InPU). Source: [266]

4.2 Methodology

4.2.1 Data collection

Case studies utilize data from both sources: primary (e.g., new data collection), secondary (e.g., already available data), of qualitative and quantitative types. It was essential to obtain as much information as possible to improve the validity and limit the effects of only one interpretation or single data source. Hence, among the diverse data collection methods, the appropriate for these study cases are interviews and questionnaires (to obtain descriptive and numerical information) and compilation of existing documents.

To have high-quality data, the collection of the LCI attempted to be precise, complete, and deviate systematically as little as possible. Also, we followed criteria consistency, coherence, and congruence of procedure for both treatment plants to maintain the data quality. Since the majority was obtained directly from officials, researchers, and engineers working at the treatment plants, data collection was derived from official information and measurements obtained directly from the AD plants. This information was necessary to quantify all the inputs and outputs of each unit process included within the system boundaries of both treatment plants. It also included and used other publications to obtain as much information as possible, creating triangulation and increasing the research's validity.

4.2.1.1 Interviews and questionnaires

This study developed interviews and written questionnaires based on inquiries from specialists or researchers in the studied anaerobic digestion plants related to waste treatment, water use, energy generation, and GHG emissions. The purpose was to handle the interviews face to face when possible; however, considering the pandemic in the course, the questionnaires were developed by a scripted questionnaire sent directly to the specialists. The specific questions designed for the interviews and questionnaires are in Annex B and C.

For the comparison of performances of the digestion plants, the questions seek to obtain qualitative and quantitative data. The purpose was to represent the quality of the processes and the resources (water, waste, and energy) and GHG emissions as a unit of analysis in quantities. The company's archives were also essential sources of numerical data and helped to obtain valuable information.

4.2.1.2 Archives and documents

Firstly, this research gathered all possible data from the companies to find any information that accomplished the Life Cycle Inventory (LCI), from technical reports, publications, meeting minutes, and previously collected measurements, available in metrics databases. Moreover, it was essential to collect secondary data from academic literature concerning these specific treatment plants and their performances. The archival data collection together with the interviews presented sufficient data to allow data triangulation. Subsequently, secondary data collection helped determine quantities and percentages of how much DAD technologies can benefit water management, waste savings, and energy systems and their NDC´s contributions.

Additionally, this research also compiled secondary information from diverse national and international entities, which have provided various studies on the topic. For example, the Institute Embrapa (Brazilian Agricultural Research Corporation), CIBiogas (International Center for Renewable Energy – Biogas), or ABiogas (Brazilian Biogas Association).

4.2.1.3 Life-Cycle Inventory

Once we obtained all the data and possible information, we developed an inventory of each system's flows, stocks, and treatment processes. This allowed having complete knowledge and understanding of the analyzed systems. Hence, the LCI methodology helped create a detailed list of inputs and outputs flows for each system. For our study purposes, the inventory flows include all substances brought into the biogas plants, such as raw materials, supply inputs, and energy, which are then processed and released as outputs to air, land, and water systems. The study designed a flow model system according to the layout of the studied treatment plants to develop this inventory and obtain any possible quantitative data of the inputs and outputs of the treatment processes more precisely. Annex B and C present the resulting LCIs. The results suggest the data per tonne throughput.

When it was impossible to have direct/primary data with exact contextual consistency from the treatment plants, this study used data from scientific literature and generic databases to reduce any possible uncertainties as much as possible, as further described in section 4.2.3.2.1.

4.2.2 Assessment Method; Multicriteria analysis

A relevant multicriteria decision analysis (MCDA) scope is necessary for this research to compare the presented options and objectively interpret the analysis results. Also, to evaluate the real advantages and benefits of one technology over the other for the treatment of OFMSW. This study proposes a methodology that integrates two analytical tools: the material flow analysis (MFA) and the analytic hierarchy process (AHP). Being the AHP is the most frequently used method for MCDA [267]. Combining these methods also allowed us to evaluate each waste management system's technical and environmental effects and assess the actual degree of improvement that the proposed solutions provide.

Hence, MFA is considered an essential component for an effective tool for waste management; being as suggested by Makarichi et al. (2018) [268], the first of four stages for an effective decision making analysis, which is: MFA, evaluation, and options analysis, MCDA, and implementation and feedback. For this study, the research centered on the two first steps and is meant to provide some technical, resource recovery, and environmental benefits analysis of both technologies. Thus, further studies are necessary for an overall MCDA. A more precise MCDA must include other criteria such as Capital Expenditure (CAPEX), cost-benefit analysis (CBA), availability of technologies, and dissemination factors. The CAPEX study shall be relevant to find the economic viability of a project.

Thus, this analysis presents the following criteria based on the MFA technique: waste collection burden, effective recycling rate, energy recovery and fertilizer recovery as an additional benefit, and mitigation potential of GHG.

4.2.2.1 Material Flow Analysis

MFA is a helpful analytical tool to identify the accumulation and depletion of materials in natural and anthropogenic environments. If properly developed it help in linking resources management to environment and waste management practices [269]. It has been used widely as a robust tool to investigate flows and stocks in MSW pathways to develop solid database analysis for waste management systems to aid and guide decision-making [270] in [268]. The primary purpose of an MFA is to create simple and reliable models to picture the reality of the studied systems [269]. This method, together with MCDA, helps to provide alternatives in a transparent, repeatable, and objective manner, which also gives room for improvement in future decision-making cycles [268].

This study implements material flow analysis as an analytical tool to map and quantify the flows and stocks of goods, substances, and energy throughout the waste treatment systems to analyze and compare the case studies. It also allows this study to highlight the issues of one technology over the other and identify the opportunities for recycling, resource recovery, and environmental impacts and benefits.

MFA approaches operate on the principle of mass balance that materials cannot be lost, drawn from the first law of thermodynamics, which entails the conservation of matter and energy. Hence, based on a spatial and temporal system boundary, the summed inputs must equal the outputs plus the stocks [268]. As illustrated in the following equation [269]:

$$\Sigma\ \dot{m}(input) = \Sigma\ \dot{m}(output) + \dot{m}(stock)\ ki\ ko \quad (1)$$

Where ki and ko represent input and output flow, respectively, and $\dot{m}$ represent the flows.

MFA applies to any combination of goods and substances, inputs and outputs, and flow magnitudes and processes of the systems; these are quantified and mapped using the software tool STAN as recommended by Graedel (2019) [271]. The analysis also provides the basis for the estimation of carbon dioxide equivalent emissions. The terms and definitions of MFA are according to the Practical Handbook of Material Flow Analysis [269].

This research developed the MFA cases to evaluate the performance of the waste treatment case studies and determine their efficiency by the following steps, as suggested by Brunner & Rechberger (2005) [269]:

(1) Definition of the problem and goals;
(2) Detect and select the stocks (goods and substances), processes and flows, scale and boundaries of the systems;
(3) Evaluation and assessment of the mass flows of goods and substances;
(4) Calculation of stocks and flows, considering all data uncertainties, and;
(5) Presentation of results.

The upcoming chapters further describe in detail these steps. Furthermore, for the case of the determination of the energy flows and stocks also analyzed, the methodology implemented was the Energy Balance further described in section 4.2.4.2.

4.2.2.2 Analytic Hierarchy Process

This research utilizes the AHP method to consider objective and subjective criteria to analyze, evaluate and compare the case studies and quantitative and qualitative information. This analysis methodology evaluates the relative importance of its various elements by pairwise comparing the considered elements. It also facilitates comprehension of certain decisions by comparing multiple objectives with personalized weighting (Milutinović et al., (2017) [267], in Iqbal et al., (2020) [272]).

Based on diverse hierarchy levels, criteria and subcriteria define the diverse comparisons to resolve the best AD´s performance. The priority of each criterion was given according to a detailed comparison of the importance of such hierarchy levels. The following table shows the requirements to analyze and covers the parameters to check the alternatives concerning their performance.

Table 5: Hierarchy Levels; list of criteria and subcriteria

Criteria	**Subcriteria**
C1 Resource recovery	SC1 Digestate (nutrients) production
	SC2 Water requirements
C2 Energy efficiency	SC3 Biogas/biomethane production

	SC4 Electricity balance
	SC5 Heat balance
C3 Environmental impact	SC6 Direct CO_{2eq} emissions
	SC7 Overall GHG savings potential
C4 Technical	SC9 Others

To carry out such analysis, and based on the procedure suggested by Pedroso et al. (2018) [273]; the research proposes the following steps:

1. Define the decision problem
2. Define the set of criteria and subcriteria
3. Define the data sources
4. Data collection
5. Pairwise comparison of criteria and subcriteria to establish the hierarchy of importance
6. Define the functional unit
7. Configure the data obtained to match the functional unit requirements
8. Calculate the performance of each alternative versus each criterion and subcriteria
9. Calculate the global index

4.2.3 Data analysis and interpretation

The purpose of the data analysis is to compare the obtained information based on the AD systems' inputs and outputs, describe the differences between DAD and WAD systems, and find out their resource efficiency and energy & environmental performances. Hence, the objective of this analysis is to derive conclusions keeping a transparent chain of evidence. For this purpose, this methodological step carries out a material flow analysis for each case study from the qualitative and quantitative data obtained in parallel to detect different patterns or correspondence, which shall be sufficiently contrasting to get meaningful results. Hence, the results of such MFA focus on evaluating the systems to determine their resource recovery potential, energy balance performance, GHG emissions, and other environmental impacts.

This strategy uses standard tools such as word processors, spreadsheet tools, and Software systems for managing the data. The technique for this analysis is tabulation, where the obtained data is arranged in tables to have a general overview of the LCI.

According to Eisenhardt (2014) [274], the key to a robust cross-case comparison is looking at the data in many divergent ways. One strategy implemented was the selection of categories and looked for similarities and intergroup differences. Another approach, also suggested by the same author, was to obtain data from diverse data sources, which allows to exploit each source's unique insight and find patterns between them. These cross-case tactics forced the research to go beyond initial impressions and strengthen and better grounding findings.

4.2.3.1 Systems definition

4.2.3.1.1 System boundaries

The system boundaries, also known as "boundary settings", are essential to MFA and help limit the stocks and flows assumed to influence biogas treatments significantly. They ideally identify, define and quantify the elementary input and output flows at the point of the treatment plants boundaries [275], including the overall quantities of emissions and products.

For this analysis, the system boundaries were defined explicitly according to the space and time of each case study, attempting to delimit uniformly all systems for the comparison purpose of this research. Thus, acknowledging the complexity of the overall system, the boundaries for both treatment plants include all activities from the delivery of the OFMSW to the plant site, heat and electricity, until the management of the main product outputs: Electrical and heat energy, or biomethane; water and humus compost; but no the transportation in and out the site, and final use of them avoiding problems in boundary definition. This research also calculated the greenhouse gas emissions and included them in the system. This analysis also attempted to set equally the boundaries for both systems, which helped both systems to be comparable and exclude any other externalities that do not relevantly affect or intervene in the OFMSW treatment process. Figures Figure 16 and Figure 17 show the system boundaries of both treatment plants.

4.2.3.2 Stocks and flows

For this project, the stocks and flows investigated in the waste treatment systems are organic waste fraction, nutrients, water, energy, and the carbon dioxide equivalent (CO_{2eq}) emissions that may arise from the processes delimited by the system boundaries.

For each system the study developed an inventory analysis, where it presents all energy and material flows. The most relevant substances and goods that originated throughout the treatment processes were identified, followed by the energy/material balances and CO_{2eq} emissions calculations. There was an emphasis on materials and energy flows based on those that cause the most relevant environmental impacts, resulting from the analyzed treatments' emissions and outputs. The following table shows the indicators and parameters considered for each impact category.

Table 6. Material Flow Analysis indicators and parameters

Inputs	Outputs	Unit indicator	Inventory parameters
1. Materials	1. Biofertilizers/ nutrients	t/year & m^3/year	Compost, digestate and materials
2. Energy	2. Energy footprint	kWh/year	Electricity, heat, diesel
3. Water	3. Water	Lit/year	Water
	4. GHG emissions	CO_{2eq}	CO_2, CH_4, N_2O

For the analysis of the GHG emissions, the following calculations are important:

- Direct CO_{2eq} (CO_2 + CH_4, + N_2O) emissions due to energy consumption;

- Saved CO_{2eq} emissions due to energy production;
- The overall saving potential; and CO_2 savings ratio.

Aside from carbon dioxide, the CO_{2eq} includes methane (CH_4), nitrous oxide (N_2O) emissions, which are the three greenhouse gases produced by a biogas plant with significant possible environmental impact. These results determine the change in the climate, considering the global warming potential (GWP) factor, which is 1 for CO_2, 28 for CH_4, and 265 for N_2O, according to the IPCC Sixth report [276].

Complementarily, as suggested by Turner et al. (2016) [277], the LCA method was used as a reference to nourish this MFA and provide valuable additional information about the environmental performance of the systems.

4.2.3.2.1 Key assumptions, limitations, and data uncertainties

The analyses and comparison of the performance of both systems: DAD and WAD, consider the general conditions of Southeast Brazil for the amounts and types of OFMSW generated and treated. Hence, resulting in the following assumptions and limitations within the established system boundaries.

Key assumptions

OFMSW Characteristics: The OFMSW entering the system has "zero burdens", as it is illogical and out of scope to account for the life cycle of each waste item in the stream, as pointed out by Gentil (2010) [278] in Iqbal (2020) [272].

Secondary products: The effects and impacts of secondary products such as diesel, oils, and others used throughout the operations were also excluded due to their none or insignificant amounts.

Analysis units: The research normalized all units having the same functional unit for the comparative analysis between the two systems. The amount of OFMSW considered for the calculations was 1 tonne of treated OFMSW per day.

Transportation: As portrayed in the system boundary diagram, in figures Figure 16 and Figure 17, the collection and transportation emissions were not considered because driving distances have an extensive variance range between the two plants.

Construction: The construction emissions and impacts of the biogas plants were disregarded in this study to have equal comparative means.

Impact categories: It is relevant for the environmental impact analysis to point out that this research considers the most relevant environmental indicators directly related to the energy and material systems; and disregard other possible environmental effects such as noise, odors, dust, acidification, eutrophication, toxicity potential, and ammonia emissions. An LCA study could further analyze these effects.

Methods and parameters: These are equivalent methods and parameters for performance, system boundaries, data quality, allocation, and assessment rules of inputs and outputs [275]. Hence, the results section clearly describes any additional function considered just for one of the two systems.

Limitations: This analysis does not consider costs and excludes any capital and financial goods since data was not delivered or available and did not directly affect the comparative analysis.
The high calorific fraction (HCF) values of the organic fraction were disregarded in these analyses.

Uncertainties

Considering the relevance of having clarity throughout the analysis and a robust MFA, the research attempted to present all data uncertainties faced during the process and reduce as much as possible any subjectivity in characterizing the dataset—this, trying to facilitate reliable databases for possible future analysis or research.

The MFA analyses provide comprehensive information about any uncertainties throughout the systems. Considering that data is often scarce or incomplete in practice, some numerical values were assumed using educated guesses and plausible reasoning, as also recommended by Laner et al., 2016 [279], bringing some uncertainties. Hence, this study also quantifies and determines any raised uncertainties. For this, the research by Laner et al., 2016 [279] is applied; the author suggests a step-wise procedure to consider any uncertainty in MFA systematically.

Another fact that caused some uncertainties in developing these case studies was the changes and modifications in the treatment processes resulting from the pandemic in course. Thus, due to this situation, the current ongoing treatment processes may vary from the quantities of residues treated, the operational practices, transportation routines, and energy consumption. However, since this condition applies for both studied cases, and this research obtained most of the data considering the situation pre-pandemic, it allows for an even comparison, which ultimately results in a fair determination of the advantages and disadvantages of both technologies, even when the current or future conditions might be different to what is at this moment.

Some of the collected data resulted from the general knowledge of the managers and operators of the treatment plants. This resulted in the variability of some flows (digestate or biogas production), recirculation rates or substrate characteristics, and the operational limitations faced throughout the monitoring processes.

4.2.3.2.2 STAN

The Software STAN v2.5 developed at the Vienna University of Technology served to conduct the MFA analyses. This system is freely available software that allows for visualization of complex MFA systems, model the processes, consider data uncertainties, and include several characteristics for the development of mass balance analysis [280]. Using this software also allowed to organize and analyze the data inventory.

4.2.4 Impact categories

The impact categories represent significant resources and environmental aspects, in which the LCI as a base for the MCA can be classified [275]. For the many possible impact categories, the main chosen for this study are mass flow and nutrient balance, energy balance, and greenhouse gas emissions mitigation. The selection of these categories was determined by: (1) their relevance within the systems for a through system comparison for the MFA and AHP; (2) the influence they have on the environment due to their outputs and emissions; and (3) also considering similar studies that represent the relevance of these categories and parameters for a reliable analysis. Hereafter is a general description of each of these impact categories.

4.2.4.1 Mass flow and nutrient balance

MFA is an appropriate tool to investigate the performance of flows and stocks of any material-based system. It is a valuable tool for analyzing substances because it can precisely determine the elemental composition in a waste treatment system [269]. The selection of substances relevant for this MFA targeted to attend the objectives of this research. This selection also relied on the scope, provided information, grade of precision, and available resources for these MFA studies. It thus was deducted by grouping all import and export flows within the delimited system into solids, liquids, and gases. This classification was always intending to cover at least 90% of the total mass flow of each group, making sure that the critical flows and stock are known, which resulted in a set of important flows of goods for both systems. Also, any substances that represented a value of less than 1% of the total system were neglected, as recommended by Brunner & Rechberger (2005)[269]. The research ensured that none of the possible small flows contribute to a later stage of the processes. If that is the case, the substance was thus considered within the analyzed system. Moreover, experience shows that many systems can be reliably characterized by a small number of substances, such as about five to ten elements [269].

Figures Figure 16 and Figure 17 show the flows and stocks of the analyzed systems. Hence, after defining the substances and system boundaries, a first rough balance of the systems was carried out for each case. All the information for each substance and flow was obtained from the available company publications and reports, their data, and other articles, always attempting to get as much as possible data to create triangulation and validate it. The data had to be reviewed and assessed in some cases, contacting officials from both companies to certify the provided information. Nevertheless, as previous studies had demonstrated, such as the one carried out by Börjesson & Berglund (2006) [281], production means for biogas systems are complex to study. Hence, this research´s analyses always attempted to normalize the functional units to be comparable and obtain precise results. In the few cases where data was unavailable, we made some assumptions, as described in section 4.2.3.2.1.

The selected goods and substances detected throughout the treatment processes were identified and listed in the following table.

Table 7: Goods, substances, and energy processed throughout the treatment systems

Process	**AD1: Wet fermentation**		**AD2: Dry fermentation**	
	Operation	**Goods, Substances, and energy**	**Operation**	**Goods, Substances, and energy**
Disposal	Patio	Leachate	Patio	Fresh Leachate
Waste preparation and pretreatment	Pretreatment & Mixing tank	-	Percolate treatment Inoculum Production Unit (InPU)	Coarse solids & sands Effluent & biofertilizer
Anaerobic digestion	Wet biodigester	Solid biofertilizer Liquid biofertilizers	Dry biodigester	Leachate Solid biofertilizers Coarse residues
Post-processing/biogas valorization	Biogas refining Biomethane storage *Alternative Option* Generator CHP	Biomethane Electricity Thermal energy	Desulfurization Biogas refining Generator CHP *Alternative Option* Biomethane storage	Electricity Thermal energy Gaseous pollutants Biomethane

4.2.4.2 Energy balance

The energy balance is a methodology widely used to analyze waste treatment systems to determine the energy footprint of their processes and represent the fossil energy demand in terms of primary energy use [282]. The input energy measures from black and brown coal, crude oil, and natural gas, and the resulting output production of electricity, heat, or fuels from the system. For this, the primary energy flows in both cases were identified and accounted from an energy balance perspective. This analysis also allowed to determine the extra energy, i.e., electricity and heat, or biomethane, to supply the internal needs, generating profitable revenues [283].

Hence, to evaluate the energy balance of both systems, the study includes the energy contained in the raw materials, recovery, conversion, and transportation technologies that operate within the system boundaries of the treatment plants. As seen in figures Figure 16 and Figure 17, each system identified, calculated, and analyzed the stocks and the flows. The energy required to collect and dump the substances outside of the system boundaries is considered negligible.

The calculations and their equivalence between energy inputs and outputs were automatically performed in the software STAN, validating their correspondence. For correspondence, this research considered as inputs and outputs the electricity and heat that are implemented and produced in the CHP processes (in the case of AD2) and their hypothetical production for the CIBiogas plant (AD1). Both energy products could be utilized within the treatment plant. In the case of electricity, it could also be fed into the grid and also be energy wise independent. In order to be comparable, this study assumes the same CHP efficiency rate to produce heat and electricity for both plants. Using the efficiency value of the CHP installed in the AD2 we know that the CHP can produce heat and electricity in a rate of 4.5:1, respectively. Thus, this same rate is assumed for the AD1, which results in an even comparison.

An alternative case was also analyzed, where biogas is turned into biomethane, considering that the CIBiogas plant already does. Figure 18Figure 19 show these energy flows and stocks throughout their primary processes. In case biomethane is produced in the AD2 plant there would be an extra energy consumption, which must be considered in the energy balance and is not taken into account in this study.

Accordingly, to effectively compare both systems, a typical approach of consumption to production was adopted, followed by an energy analysis and determining the energy ratio (ER). This ratio is the sum of all energy inputs into the systems, divided by the energy obtained by the biogas generated. Thus, the results show the system's efficiency, considering that the higher the ER, the less efficient the system is; i.e., when the ratio is higher than 100%, there is more consumption than energy production.

The Energy input/output ratio (ER) is determined with the following formula:

$$Energy\ {}^{i}/_{o}\ ratio = \frac{Energy\ Inputs}{Energy\ outputs}$$

Where:

Energy i/o ratio (ER)	= Percentage of energy consumed during the treatment process out of the overall energy produced.
Energy input	= Sum of electricity, heat, and diesel consumed throughout the treatment process in kWh/year.
Energy output	= Sum of electricity and heat produced from biogas in kWh/year.

For the specific case of thermal energy, it can hardly be transported in any way or only in short ranges, which means that the heat produced can be used in a limited number of applications [275]. In the case of the TMethar plant, the managers intend to use the heat produced to heat the biodigesters to reach thermophilic temperatures. For the IPU plant (AD1), however, the plant managers have not considered heat use until now.

4.2.4.3 GHG Emissions mitigation

Reducing emissions of greenhouse gases is one of the main reasons for implementing biodigesters to effectively treat the OFMSW, and hence diverting its disposal from landfills and dumpsites [284]. The utilization of GHG instead of releasing them to the environment contributes to clean releases of these and other contaminant gases and replace the fossil fuels otherwise utilized to produce energy. It is usually represented as the GHG mitigation potential, which is also a standard parameter considered for environmental impact assessments of MSW. Around 96% of all reviewed articles by Iqbal et al. (2020)[272] consider this impact evaluation as an attribute to the issue of climate change.

To determine the GHG mitigation potential of the studied systems and accomplish the objectives of this study, an analysis was carried out considering the following calculations:

- Direct CO_{2eq} emissions due to electricity consumption;
- Direct CO_{2eq} emissions due to CH_4 uncontrolled emissions;
- Direct CO_{2eq} emissions due to energy production;

- Saved CO_{2eq} emissions due to energy production;
- The overall GHG saving potential and CO_2 savings ratio.

To determine the CO_{2eq} factor for each different gas emission or savings, this research paired and normalized the quantities multiplying the calculated emissions by their GWP factor. Even when anaerobic digestion is associated with the production of several gases, carbon dioxide, methane, and nitrous oxide are the main contributors to global warming.

Thus, the following GWP for a 100 years' time horizon, as suggested by the Sixth IPCC Report [276]:

Gas	***100-year GWP***
CO_2	1
CH_4	28
N_2O	265

The project CO_{2eq} emissions are calculated with the following equation:

$PE_{AD} = PE_{EC} + PE_{CH_4} + PE_{EP}$

Where:

PE_{AD} = Total project CO_{2eq} emissions
PE_{EC} = CO_{2eq} emissions from electricity consumption
PE_{CH_4} = CO_{2eq} emissions from CH_4 uncontrolled emissions
PE_{EP} = CO_{2eq} emissions from energy production

4.2.4.3.1 Direct CO_{2eq} emissions from electricity consumption (PE_{EC})

With this parameter, this research determined the CO_{2eq} emissions considering the CO_2, CH_4 and N_2O released during energy consumption throughout the treatment systems. To calculate and set a comparable number within the systems, the calculations considered the so-called "emission factor", which sets the emissions of GHG´s per 1 kWh produced of electricity, which was developed by Bander et al. (2011) [285] for the specific Brazilian case. Thus, GHG´s released from electricity consumption were determined for the whole process within the established system boundary.

These emissions were calculated with the following equations:

$PE_{EC} = CO_2 + CO_{2eq}\ from\ CH_4 + CO_{2eq}\ from\ N_2O$
PE_{EC} = (EleC X CO_2 GWP X CO_2 EF_{EC}) + (EleC X CH_4 GWP X CH_4 EF_{EC}) + (EleC X N_2O GWP X N_2O EF_{EC})

PE_{EC} = CO_{2eq} emissions from electricity consumption
CO_2 = CO_2 Emissions
CO_{2eq} from CH_4 = CO_{2eq} emissions from methane

CO_{2eq} from N_2O = CO_{2eq} emissions from nitrous oxide
EleC = Electricity consumption (kWh/year)
GWP = Global Warming Potential of each GHG for a 100-year time horizon
EF_{EC} = Emission factor per unit of kWh energy consumed of each GHG (as per *Table* 8).

The following table shows the emission factors per unit of kWh consumed:

Table 8: Emission factors per unit of kWh consumed for Brazil. Source: [285].

	Emissions per 1 kWh of electricity		
Electricity	0.1099074 kg CO_2	0.0000021158 kg CH_4	0.00000064114 kg N_2O

4.2.4.3.2 Direct CO_{2eq} emissions from CH_4 uncontrolled emissions (PE_{CH_4})

Project emissions of methane associated with the anaerobic digester depend on several factors such as the management of the digestate, biodigesters technologies, among others. These occur due to incomplete combustions in the CHP systems, physical leaks through the equipment or engines, emissions associated with storage and composting of the digestate and biogas, among other causes [286].

Different authors propose diverse fugitive emissions rates such as 3.5% according to the Danish EPA, 1997 in Reeh & Møller (2001) [287]; or 2% by Börjesson & Berglund (2006) [281]. For this study, considering the impossibility of measuring or obtaining precise data on both plants, we supposed a CH_4 emission of 1% of the produced biogas for both cases, to be comparable. It is also worth mentioning that these emissions should be kept low because if they increase to 2%, the GHG mitigation benefits would be lost, considering that CH_4 is 28 times more contaminant than CO_2.

4.2.4.3.3 Direct CO_{2eq} emissions from energy production (PE_{EP})

Just like any other combustion process, energy conversion of biogas in a regular CHP gas Otto-engines releases gaseous emissions to the environment [275]. Some standards have been set for different emissions sources to estimate and control any hazardous effects of these emissions [275]. Thus, the following information was considered for the dimensions and characteristics of the studied biogas plants:

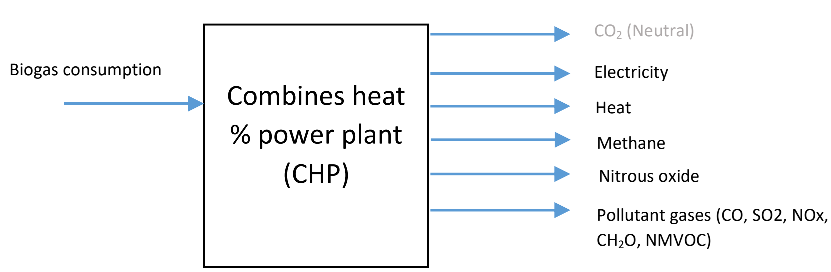

Figure 15: Inputs and outputs of a CHP unit. Source: adapted from [288].

The GHG´s mainly released after the combustion of biogas are CO_2, CH_4, N_2O. Along with these GHG´s, biogas combustion releases other air pollutants to the environment and atmosphere. An LCA and an environmental analysis should consider these gas releases to evaluate the actual environmental performance of the biodigesters. Carbon monoxide (CO), nitrogen oxides (NO_x), and Sulfhydric acid (H_2S) are the primary pollutants emitted during the combustion processes and with significant possible environmental impacts. The following table presents the amount of these emissions and others per kWh according to Paolini et al. (2018) and Di Maria and Sisani (2017) [257,284].

Table 9: Emission factors: Direct emissions in the air of internal combustion engines per 1 kWh produced. Source: [257,284].

CO bio (mg)	916.3
N_2O (mg)	47.73
NO_x (mg)	285.4
NMVOC (mg)	38.17
Pt (ng)	133.6
SO_2 (mg)	478
CH_2O (mg)	50.4

For the specific case of direct CO_2 emissions released from the fermentation processes of the biomass, and the combustion in the CHP engines are neutral in this analysis since the carbon emitted is biogenic and comes from plant residues which are carbon fixing systems, usually reaching a balance. These gases releases occur as the natural carbon cycle [257]. CH_4 is released from incomplete combustion, and throughout the energy, production processes are included in the previous section as CH_4 leakages.

The GHG mainly considered for this parameter is N_2O, which has a high GWP and can result in a significant greenhouse effect [257]. It was calculated with the following formula:

$PE_{EP} = CO_{2eq} \text{ from } N_2O = EP \times N_20 \; EF_{EP} \times N_2O \; GWP$

CO_{2eq} from N_2O = CO_{2eq} emissions from N_20 for energy production
EP = Energy production (kWh/year)
EF_{EP} = Emission factor of N_2O per unit of 1 kWh produced
GWP = Global Warming Potential of N_2O for 100-year time horizon.

4.2.4.3.4 Saved CO_{2eq} emissions due to energy production (ES_{EP})

This research calculated the amount of GHG emissions saved due to the substitution of fossil fuels with electricity, heat, and biomethane. The calculations relied on unifying the CO_{2eq} values considering the emissions factors suggested by Brander et al. (2011) [285], found in the following table.

Table 10: Emission factors per unit of 1 kWh generated. Source: Brander et al., (2011) [285].

	Emissions per 1 kWh of electricity		
Electricity	0.092643638 kg CO_2	0.00000178354 kg CH_4	0.00000054043 kg N_2O

The following formula served to calculate this rate:

$$ES_{EP} = CO_{2SAV} + CO_{2eq} \text{ from } CH_{4\,SAV} + CO_{2eq} \text{ from } N_2O_{SAV}$$

$$ES_{EP} = (EnP \times CO_2\ GWP \times CO_2\ EF_{EP}) + (EnP \times CH_4\ GWP \times CH_4\ EF_{EP}) + (EnP \times N_2O\ GWP \times N_2O\ EF_{EP})$$

ES_{EP} = Project CO_{2eq} emissions saved from energy production
$CO_{2\,SAV}$ = CO_2 Emissions saved
CO_{2eq} from $CH_{4\,SAV}$ = CO_{2eq} emissions from methane saved
CO_{2eq} from N_2O_{SAV} = CO_{2eq} emissions from nitrous oxide saved
EnP = Energy (electricity and potential heat) production (kWh/year)
GWP = Global Warming Potential of each GHG for 100-year time horizon.
EF_{EC} = Emission factor per unit of kWh energy produced of each GHG (as per

Table 10).

The analysis considers these same emission factors for the generation of thermal energy. Considering that data was limited for this specific thermal energy factors and as stated in Brander et al. (2011) [285], the difference with the IEA composite electricity/heat factor for kgCO2/kWh is of only 4.3%. Thus the variance is tolerable.

Additionally, CO_{2eq} emissions can be saved in AD by reducing the otherwise GHG´s emitted by regular practices such as dumpsites or landfills. It shall also be pointed out that these and other GHG emission indirect savings such as the soil improving effect, crediting carbon in the digestate, or peat substitution are not considered in this study due to practical purposes. Aside from being outside the studied system boundary, these factors are too versatile and more dependent on the organic matter´s physical and chemical conditions. Thus, there is the need for a further and more specific study that focuses on these aspects.

4.2.4.3.5 Overall GHG saving potential and CO_2 saving ratio

The previously described calculations in this section were linked to determine the total GHG savings potential for both waste treatment scenarios. Aside from this factor, the CO_{2eq} savings ratio (CO_2_SR) was also calculated, representing the relation between the CO_{2eq} emitted and the CO_{2eq} saved; calculated with the following formulas.

$$Savings\ potential\ (SP) = \mathrm{ES_{EP}}\ (\mathrm{or}\ CO2\ eq.saved) - \mathrm{PE_{AD}}\ (or\ CO2\ eq.emitted)$$

$$CO2\ savings\ ratio\ (CO2\_SR) = \frac{\mathrm{PE_{AD}}\ (or\ CO2\ eq.emitted)}{\mathrm{ES_{EP}}\ (\mathrm{or}\ CO2\ eq.saved)}$$

Where:

Savings potential (SP)	= CO_{2eq} total emissions saved minus CO_{2eq} total emitted
CO_2 savings ratio (CO_2_SR)	= Percentage of CO_{2eq} emitted out of the overall CO_{2eq} potentially saved to be emitted
ES_{EP}	= Project CO_{2eq} emissions saved (per year)
PE_{AD}	= Project CO_{2eq} emissions (per year)

The CO_2_SR indicates the percentage that the GHG emissions represent out of the total GHG potentially saved by the AD systems. Thus, the lower the number, the more capacity the system has to mitigate GHG emissions.

4.2.5 Reporting

It is essential to present and report the results of these case studies analyses appropriately, visualizing the conclusions and facilitating the understanding for goal-orientated decisions. Having as a primary goal to make the message clear, understandable, reproductive, and trustworthy, as pointed out by Brunner & Rechberger (2005) [269]. Runeson & Höst (2009)[258], and Yin (2003)[259] also propose the following linear-analytic structure for reporting the cases studies: problem statement, related work, methods, analysis of results, and conclusions.

The results must be condensed into a clear and comprehensive manner to demonstrate the reliability of the methodology. Section 4.3 presents the numerical results and its analysis from a comparative perspective. Also, in the same section, the flows diagrams and other standard graphs help to graphically represent the materials and energy flow throughout the systems for each case study, which also functions to maximize the impact of the MFA findings and supply easily understandable information for the AHP. The conclusions are presented and addressed to the audience unfamiliar with MFA, serving as an overview of the complete analysis not using any technical jargon.

4.3 Results & discussion

This chapter presents the discussion and results of assessing the most relevant environmental burdens and benefits; the material and energy used and emitted within the studied biogas plants, delimited by the system boundaries. Also, their GHG emissions mitigation potential is calculated. It is intended to present the results transparently with tables and figures to facilitate their comparison. The selected input and output substances and units studied are shown in Table 6. To better understand and relate the diverse studied parameters, this research normalized the quantities, which also helped to directly compare both technological options, creating simple and reliable models to picture the reality of the studied systems as straightforward as possible. Furthermore, the discussion of the results was carried out following the current state of knowledge and objectively determine the advantages and disadvantages of both AD systems, according to the described conditions.

4.3.1 Mass flow and nutrient balance

The OFMSW is transported and deposited into the treatment plants and treated every day. However, the quantities of the residues treated in both plants are considerably different; with 15.6 Tonne/day of OFMSW, AD2 treats about 28 times more residues than the quantity treated by AD1 (.55 Tonne/day). Thus, to determine a comparable measurement, the data was normalized and evaluated according to the values of flows and stocks equivalent for treating one tonne of OFMSW daily for both cases. In the following Table 11 and

Table 12, the quantities of inputs and stocks of materials are presented.

Table 11: Inputs and stocks of materials and substances of anaerobic digesters

	Inputs				**Stocks**	
	OFMSW treated		**Water**		**Water recirculated** *1	
	Kg/day	*kg/tonne OFMSW*	*Lit/tonne OFMSW*	*Lit/day*	*Lit/tonne OFMSW*	*Lit/day*
AD1	550	916.67 92%	83.33 8%	50	0	0
AD2	15600	1000 100%	0	0	298.26 30%	4,652.86

For AD2: *1 Lixiviates from MESB to InPU + Liquids from FL to InPU (96% of FL)

Table 12: Outputs of materials and substances of anaerobic digesters

	Outputs											
	Solid biofertilizer		Liquid biofertilizer*1		Solid rejects*2		Water effluents		Others (Solid pollutants)		Biogas*3	
	kg/tonne OFMSW	*Kg/day*	*Lit/tonne OFMSW*	*Lit/day*	*kg/tonne OFMSW*	*Kg/day*	*Lit/tonne OFMSW*	*Lit/day*	*kg/tonne OFMSW*	*Kg/day*	*kg/tonne OFMSW*	*Kg/day*
AD1	100.92 10%	60.55	740.08 74%	444.05	0	0	0	0	-	-	159 16%	95.4
AD2	233 23%	3634.8	14.91 1.5%	232.64	232 23%	3,622.32	142 14%	2,215	1 0.1%	0.01	79 8%	1,234

For AD2: *1 Water effluent from the InPU used as biofertilizer

*2 Remaining rejects from digestate + Remaining rejects from leachate (FL)

*3 Biogas from biodigester + Biogas from InPU

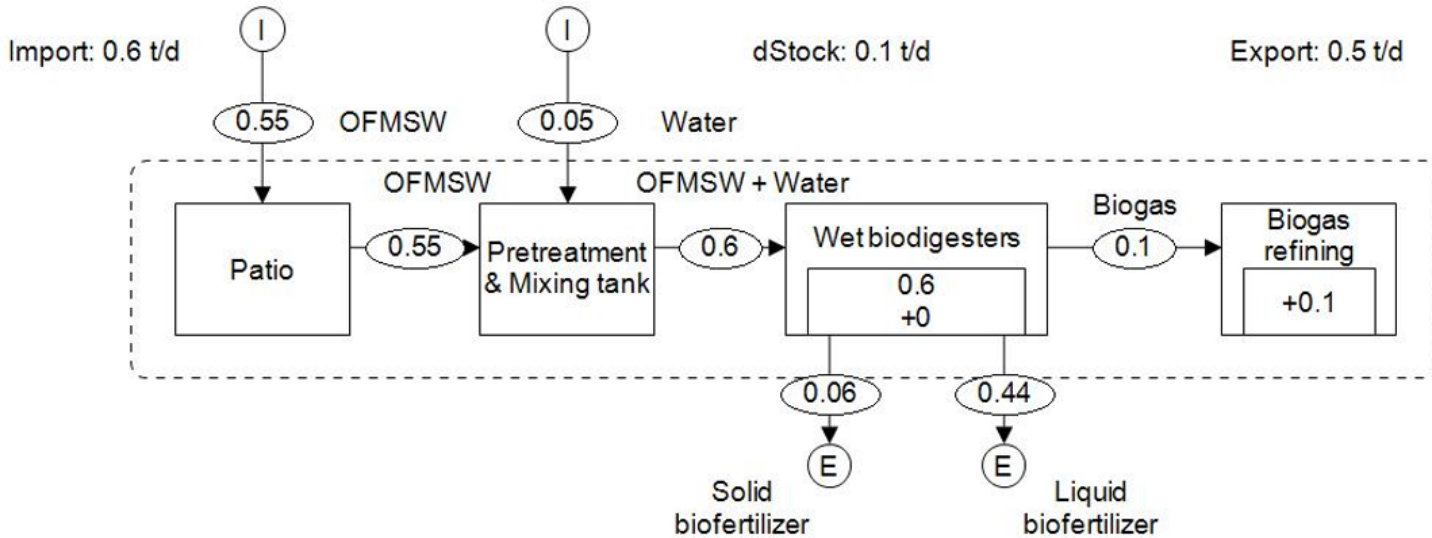

Figure 16: Consolidated MFA of AD1. Flows (tonne/day) & Stocks (tonnes)

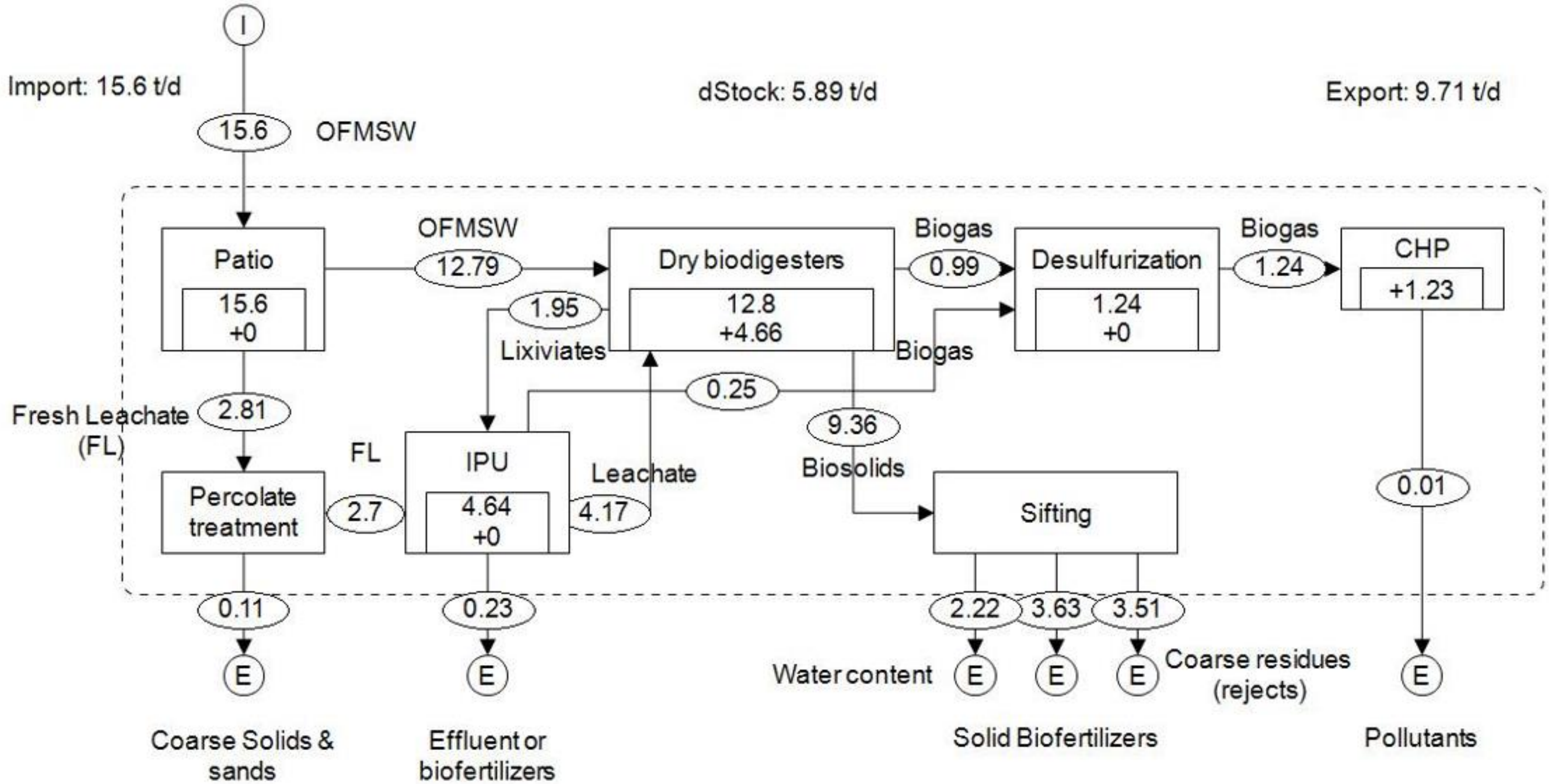

Figure 17: Consolidated MFA of AD2. Flows (tonne/day) & Stocks (tonne)

4.3.1.1 Water and leachate

Water content and production of leachates on the OFMSW vary according to the types of residues and their characteristics and climate and geography conditions, among other factors. As it can be deduced, this water content determines the requirements for its treatment in an anaerobic digester, whether it is a wet or a dry system.

For AD1, water is added to the process to reach enough fluidity for the trituration of the organic residues. The quantity variates based on the residues content and is approximately 50 liters per day (or 83.5 Lit/tonne OFMSW) accounting for about 8% of the total treated value. As for the AD2 process, no extra water is added for its treatment process; this represents one of the main advantages of DAD systems. However, as demonstrated in this analysis, the water expenses by the AD1 system are not significant but indeed considerable, representing a total of fewer than 100 liters per treated tonne of OFMSW.

In the AD2 plant, from the total OFMSW arrived at the site, approximately 18% of the total mass is composed of the fresh lixiviate, also called Fresh Leachate (FL). In this system, water gets recirculated after a general treatment at the Inoculum Production Unit (InPU) and then used as inoculum in the MESB reactors. This circuit then returns the lixiviates from the MESB to the InPU at approximately 15-20% of the total mass-loaded to the MESB reactors. This value, together with the water added after the percolation of the FL, represents 30% of the total mass and stays as a stock in the InPU system; it is continuously treated. In AD1, no water is recirculated as the digester's continuous process allows the inoculum to stay active in the biodigester and constantly activate the new entering residues. Thus, in this digester, all the liquid emitted by the system after the biodigestion process is utilized as a liquid biofertilizer, a significant treatment plant asset. This fertilizer, accounting for 74% of the emitted substances, is used to fertirigate the plantations and green areas around the treatment plant´s site.

On the other hand, it is estimated that for the AD2, even though the value varies considerably, roughly only 1.5% of the outputs are used as fertigation liquid. However, it still represents a considerable quantity of approximately 232 liters daily, which is utilized within the “Eco Park Caju” as a fertilizer of the gardens and orchards; or to correct the humidity levels of the other composting rows.

Also, in this treatment plant, approximately 2,215 liters of excess effluent per day (equivalent to 14% of the outputs) are directed to the effluent tank of the overflow station at Ecoparque Caju, which stores the effluents from the overflow shed, and then are sent to the effluent treatment station, thus enabling its safe disposal [266].

On the one hand, these results demonstrate one of the main advantages of dry systems for fewer water needs. Nevertheless, at the same time, the water utilization of WAD systems does not represent large amounts. Considering their rich nutrient contents, the resulting liquids can be utilized to fertirigate the crops or plantations around the site.

It is also worth pointing out that for the resulted digestate of AD1, there is currently no direct segregation of the solid and liquid fractions; however, this research assumed the segregation of both solids and liquids for comparative purposes of this study obtain a direct result.

4.3.1.2 Raw materials and resource recovery

As per the solid fraction, the AD2 produces almost 2.5 more solid digestate or biofertilizers than AD1, producing roughly 233 kg/tonne OFMSW (50% of all the produced digestate as solids); in comparison to the 100 kg/tonne OFMSW of the AD1. The resulting digestate can be turned into nutrient-rich biofertilizers. For the AD2, a composting facility after the methanization processes helps sanitize the solid digestate to obtain a byproduct with outstanding quality.

The AD1 system uses all the resulted solids as biofertilizers. It does not produce any solid rejects throughout the process. In the case of the AD2, around 232 kg/tonne OFMSW are generated and discarded, representing 23% of the total managed mass (the other 50% of the produced solids). However, this is attributed to the fact that AD1 accounts with a pretreatment step where residues are triturated and mixed, which demands at the same time more input of energy, resulting in the long term more expenses of energy utilization (As discussed in Section 4.3.2.4). This characteristic confirms the robustness and tolerance of impurities as an advantage that DAD present.

It shall also be pointed out for both systems that including pretreatment steps for the removal of aggregates, and particle reduction of the treated OFMSW, result in better quality biosolids or biofertilizers.

4.3.1.3 Other solid, liquid, and gaseous pollutants

Other residues are generated during the refining of the biogas. In the case of AD2, the CHP combustion system produces chemicals and emissions such as nitrous oxide, carbon monoxide, organic carbon, particulate material, sulfur dioxide, hydrochloric acid, and ammonia [266]. These emissions should be accounted for in a more specific LCA. As for the AD1, the refining process for biomethane production and pollutants removal is currently carried out with activated carbon. This treatment process results in the generation of carbon residues. However, an analysis of these is not carried out in this study. Usually accumulated substances are hydrogen sulfide (H_2S), siloxane, water vapor, ammonia (NH_3), nitrogen (N_2), oxygen (O_2), volatile organic compounds (VOCs), carbon monoxide (CO), hydrocarbons [289].

For option 2 of electricity and heat production, the contaminant gases that generate or can potentially generate during the combustion processes in the AD1 are shown in the following table. These were calculated with the emission factors presented in Table 9, section 4.2.4.3.3. Also, with the present gases generated in the CHP system of AD2.

Table 13: Direct emissions in the air of internal combustion engines. AD1 is a supposed scenario in case the CHP combustion system is installed.

	AD1	AD2	
O	66.89	474.78	kg/year
SO_2	34.89	247.68	kg/year
NO_x	20.83	147.88	kg/year
NMVOC	2.79	19.78	kg/year
CH_2O	3.68	26.11	kg/year

	AD1	AD2	
CO	0.333	0.083	kg/t OFMSW
SO2	0.174	0.043	kg/t OFMSW
NOx	0.104	0.026	kg/t OFMSW
NMVOC	0.014	0.003	kg/t OFMSW
CH_2O	0.018	0.005	kg/t OFMSW

4.3.2 Energy balance

The energy balance is attributed primarily to the energy generated and the energy consumed for an energy system. The energy requirements for the treatment of biowaste vary among each biogas plant and treated substrate [290], which applies in these case studies with high variability on their energy demands for their operations; for instance, pretreatments, pumping, mixing, maceration. This section presents the analysis of the quantities of energy consumed and produced to determine the performance of both systems.

A biodigester's energy generation rates depend on several factors such as the composition of the substrates, water contents, climate, digestion technologies, and conditions (co-digestion; batch or continuous; one or two-phase digestion), among others [290]. Other factors that can directly affect the biogas yields are the digestion temperature, retention time, organic loading rates, pre-treatment of the raw materials. These are disregarded in this analysis. Thus, even though these characteristics are indeed different for both studied cases, this research focuses on the actual biogas consumption and production rates to generally compare both case studies.

Ultimately, the energy input/output ratio was defined to directly evaluate the energy balance of both biogas systems considering the consumption of heat and electric energy and the generation of energy mainly contained in the produced biogas, as biomethane and electricity and heat.

Table 14: Energy consumption (Ei) of anaerobic digesters

	Electricity		Heat
	kWh/tonne OFMSW	kWh/day	kWh/day
AD1	1,272.73	700.00	0.00
AD2	24	374.40	0.00

Table 15: Energy production (Eo) of anaerobic digesters.

	Biogas			*Option 1* Biomethane			*Option 2* Electricity		*Option 2* Heat (inactive)		Biogas leakages		
	Nm³/tonne OFMSW	kWh/tonne OFMSW	kWh/day	Nm³/tonne OFMSW	kWh/tonne OFMSW	kWh/day	kWh/tonne OFMSW	kWh/day	kWh/tonne OFMSW	kWh/day	Nm³/tonne OFMSW	kWh/tonne OFMSW	kWh/day
AD1	290.91	1600	880.00	170.18	1882.21	1,035.22	363.64	200.00	1647.92	906.36	2.91	16 1%	8.8
AD2	55	302.5	4,719.00	33.68	372.54	5,811.66	91	1,419.60	412.39	6433.33	0.55 1%	3.02	47.19

Note: Grey numbers represent the supposed scenarios.

Table 16: Energy available and ER (Ei/Eo)

	Energy Available currently		Energy Available potential Option 1		Energy Available potential Option 2		E Ratio (Ei/Eo)		
	KWh/ton FORSU	KWh/day	KWh/ton FORSU	KWh/day	KWh/ton FORSU	KWh/day	Current	Potential Option 1	Potential Option 2
	593.48	326.42	593.48	326.42	738.83	406.36	67.6%	67.6%	63%
	Biomethane						Biomethane	Biomethane	Elect & Heat
	67	1,045.20	345.52	5,390.07	479.39	7,478.53	26.4%	6.4%	4.8%
	Electricity						Electricity	Biomethane	Elect & Heat

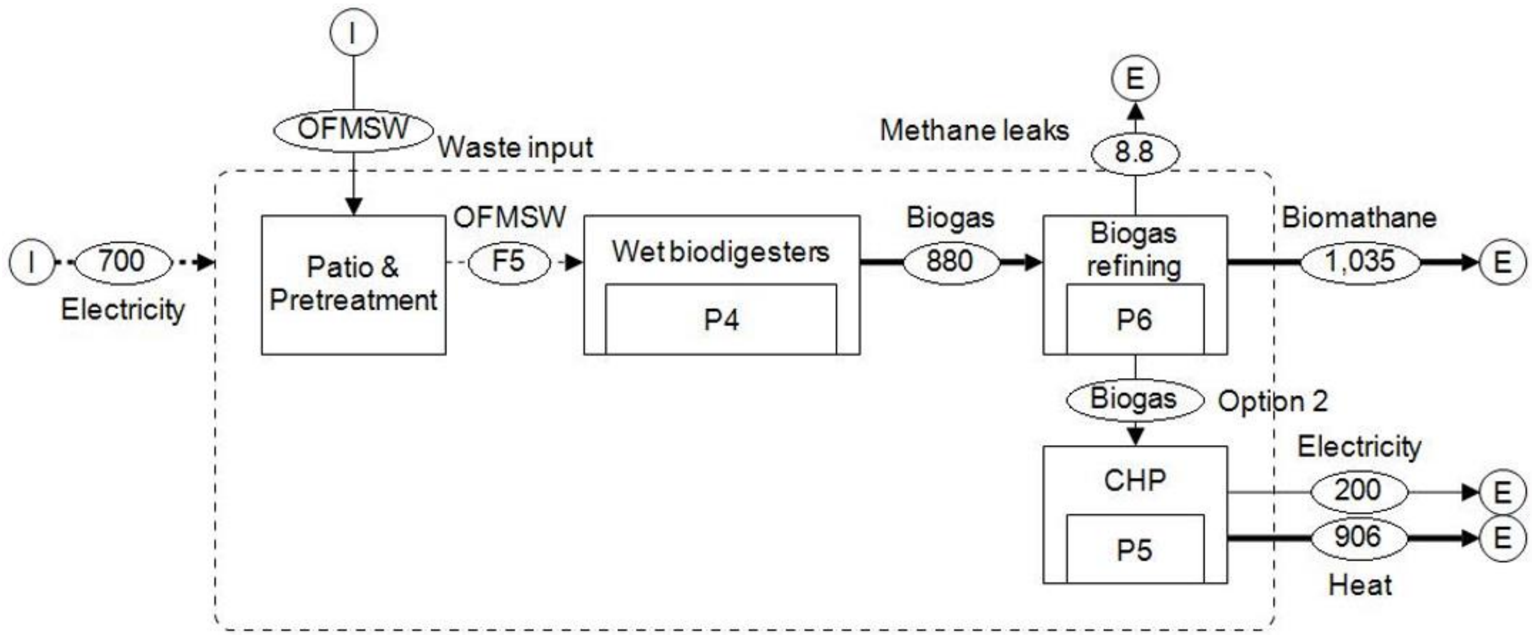

Figure 18: Consolidated EB of AD1. Flows (kWh/day) & Stocks (kWh)

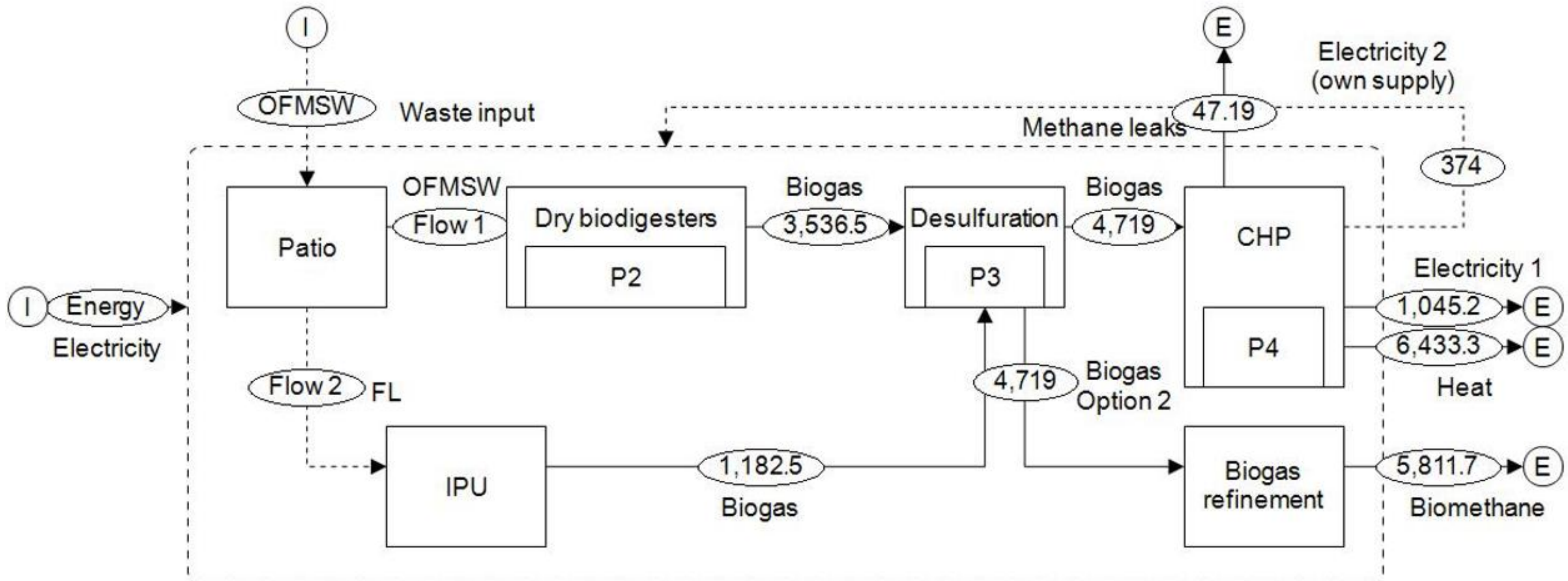

Figure 19: Consolidated EB of AD2. Flows (kWh/day) & Stocks (kWh)

4.3.2.1 Biogas

With the more significant amounts of OFMSW treated and the biogas produced from the dry biodigesters and the InPU system, approx. 643 and 215 Nm^3/day, respectively, the TMethar AD2 produces more than five times more biogas daily than the biodigesters of AD1 (160 Nm^3/day). Nevertheless, due to the biogas outputs, AD1 represents a greater energy generation rate per unit tonne of treated OFMSW. Biogas production resulted in 290.91 m3 per tonne OFMSW for the AD1 compared to just 55 m^3/tonne OFMSW of the AD2. In brief, this shows 5.28 times more biogas production capacity for the AD1. This result aligns with previous comparative studies such as [59] and [291], that present that the WAD systems often produce more biogas than DAD systems.

4.3.2.2 Biomethane

Biomethane production is already carried out by AD1, which as for AD2, is just considered an option for a future energy production expansion. The biomethane production potential for AD1 is more significant, considering that both systems present similar CH_4 contents in the produced biogas (58.5% for AD1 and 60% for AD2). The results show a potential of 170.18 m^3 biomethane production for AD1 and 33.68 m^3 for AD2 for each tonne of collected and treated OFMSW. This biomethane production represents around five times more biogas production for the WAD system. In a typical scenario in AD1, the biomethane is utilized to supply the heavy load transportation system and vehicles within the treatment plant, a situation that has varied due to the current pandemic, causing certain uncertainties as pointed out in section 4.2.3.2.1, but disregarded in this analysis.

4.3.2.3 Uncontrolled losses of methane

Losses and uncontrolled emissions of biogas usually occur during the operation of biodigesters; these are usually due to leakages from stored biogas or refining processes due to defective technology, leakages, or system inefficiencies; these cause losses on energy production and increase the GHG emissions [281].

For the case of AD1, there is a refining system of membranes filtration, which causes a loss of CH_4. Consequently, it results in a loss of approximately 2.91 Nm^3 of methane per tonne of OFMSW. For the AD2, according to the provided information, there are no methane losses registered, nevertheless considering that losses may occur during the upgrading and pressurization of biogas, for the analysis purpose of this study, this research suggests a 1% percentage as a baseline. Thus, it results in a loss of approximately 0.55 Nm^3 of methane per tonne of OFMSW. Other losses may occur in other parts of the system; however, this research does not consider them due to the difficulties in measuring and quantifying them.

Thus, to have more reliable data in the future, monitoring these methane losses is crucial to evaluate absolute GHG emissions, considering that for an average emission of 2%, the methane emissions may increase from 10 to 100 times, depending, according to [281] on the substrates and end-use of the studied technologies.

4.3.2.4 Electric energy

AD2 already has an installed cogeneration CHP system with a capacity of up to 35 KW of electrical energy, which currently produces approximately 91 kWh per tonne of OFMSW. Thus, it results in a production of 1,419 kWh of electricity per day, which suffice to supply the daily demanded 374 kWh of electricity (corresponding to 26.4% of the electricity generation capacity of the TMethar system). Thus, the plant ends up every day with an approximate surplus of 1,045 kWh, which is utilized to supply some of the energy demand of the Caju´s treatment plant or injected into the power grid.

As for AD1, electricity generation is just seen as a possible future option. The managers foresee installing a generator to produce approximately 200 kWh/day, equivalent to 363.64 kWh per tonne of treated OFMSW. This energy generation again shows the WAD system's significant potential, which demonstrates around four times more electricity potential production per tonne of OFMSW than what is currently produced in the DAD system. However, even with the excellent electricity production performance of AD1, its disadvantage comes when the energy consumption by the plant is considered. In this plant, 700 kWh are supplied every day (1,273 kWh/tonne OFMSW) by Itaipu Binational to maintain the plant running. This energy goes mainly to the pumping and mixing systems, which demand considerable amounts of electricity. Consequently, even when AD1 is much smaller, it consumes more electricity than AD2. This energy performance is further analyzed as the energy input/output ratio.

4.3.2.5 Thermal energy

In regard to thermal energy, the treatment plants neither produce nor consume thermal energy for their processes. However, there has been real potential for this energy resource. In the AD2 plant, for instance, although the methanization equipment is configured to perform the thermal exploitation of biogas, this operation is not yet carried out. The possible heat to utilize in this plant depends on the operating temperature of the bioreactors (mesophilic and thermophilic); and the desired degree of drying for the digested material. Thus, the thermal energy can be used to dry and sanitize the digested material (MD) to reduce the volume of the waste sent to landfills; and internal heating of the InPU. In this plant, potentially 6,433.3 kWh/day could be generated of thermal energy; equivalent to 412.4 kWh/tonne of OFMSW.

In the case of AD1, biomethane is currently the only wanted bioenergy. However, a plan is to install a CHP cogeneration system, potentially supplying thermal energy to the treatment plant. Thus, in order to be comparable, this study assumed the same the efficiency value of the CHP installed in the AD2, producing heat and electricity in a rate of 4.5:1, respectively. Thus, for this plant, the potential production of thermal energy resulted in 906.36 kWh/day; equivalent to 1,647.92 kWh/tonne of OFMSW. Nevertheless, it must be mentioned that there are still no directions towards implementing this system.

4.3.2.6 ER

The energy input/output ratio results from the sum of the primary energy input into the biogas systems, divided by the energy content in the biogas produced. The higher the ratio, the less energy efficient the biogas system and vice versa. This ratio helps this analysis to relate and directly compare the energy performance of both systems, with both options biomethane production, and electricity and heat production.

The results disclose the current energy efficiency of the AD2 system, even though it produces less energy than AD1. i.e., for the AD2 from the total electric energy produced contained in the biogas directly, 26% is utilized for the internal usage; whereas for the AD1, the energy consumed represents about 68% of the total energy produced. This variance is attributed to the fact that AD1 demands large amounts of energy for its pumps and mixing systems operations. That is to say that even when AD1 produces a considerable large amount of energy (1,882.2 kWh/tonne OFMSW of biomethane) with little organic matter (.55 Tonne/day), the fact that it demands large amounts of electricity (1,272.7 kWh/tonne OFMSW) for its operations and maintenance reduce its energy balance efficiency, resulting in an ER of 67.6%. On the other hand, the low energy demands by the AD2 (24 kWh/tonne OFMSW) and its electricity production (91 kWh/tonne OFMSW) represent currently an ER of AD2 (26.4%), which demonstrate its already energy efficiency.

Furthermore, this efficiency could be further improved utilizing its overall energy potential either converting biogas to biomethane (Option 1) or utilizing the thermal energy (Option 2) resulted from the CHP system. For this, the 1rst option of biomethane production, the AD2 plant reaches a production of 345.5 kWh/tonne OFMSW resulting in an ER of 6.4%. However, in case biomethane is produced in this plant there would be an extra consumption of energy, which is unknown and not considered in this study. In the case of AD2, the plant already consumes as previously mention, around 68% of the total energy produced.

The Option 2 of electricity and thermal energy production in the CHP unit also shows the efficiency of AD2 considering that in the case that the plant utilizes also its thermal energy produced; the consumption of energy within the plant would represent only around 4.8% of the total energy production. On the other hand, in the case a CHP unit (with similar characteristics) was implemented in AD1, still the plant would consume 63% of all the energy it would produce.

This results can also help to deduce that in case all energy produced by the CHP system in both plants was thoroughly utilized, to satisfy the plant energy needs and sending the surplus to the city energy grid, it would be energy wise slightly more efficient than the production of biomethane, as represented by the energy ratios shown in Table 16.

In addition to the presented energy savings, there are also the indirect energy savings obtained with the replacements of activities and systems of the inputs and outputs; for example, the indirect energy savings due to the improved utilization of plant nutrients with the biofertilizers [290]. These are not calculated in this analysis.

Both treatment plants present opportunity areas for improving their energy performance. They are also climbing up on their learning curve, and new practices and technologies could be implemented to produce more energy with the less possible resources. Also, to modify their operational functions, considering that the operational functions of most biogas plants correspond to up to 50 to 80% of the total energy input [290].

4.3.3 Emissions and global warming

To evaluate and compare the GHG mitigation potential of the analyzed AD systems, this research determined and summed up the more significant CO_{2eq} emissions by electricity consumption (from the main greenhouse gasses CO_2, CH_4, N_2O), the CH_4 uncontrolled losses, and energy production processes. For a realistic scenario, this approach considers two optional processes; biomethane production (already practiced in AD1) and electricity and heat production (electricity already produced in AD2). The CO_{2eq} emissions saved from energy production were also calculated and compared with the previously estimated direct emissions. Overall GHG saving potential resulted from these calculations, which allowed for a deduction on the GHG mitigation efficiency for both systems. The results are as follows:

Table 17: Total project CO_{2eq} emissions.

	CO_2	***CO_{2eq} from CH_4***	***CO_{2eq} from N_2O***	***TOTAL CO_{2eq}***			
Option 1: Biomethane		kg/year		kg/year		kg/tonne OFMSW	
AD1							
Electricity consumption	28,081.34	15.14	43.41	28,139.89		*140.17*	
CH_4 leakages	-	12,264.00	-	12,264.00	***40,403.89***	*61.09*	***201.26***
Biogas refining	122,056.00	-	-	-		*0.00*	
AD2							
Elect. consumption	14,903.44	8.03	23.04	14,934.52		*2.62*	
CH_4 leakages	-	65,005.92	-	65,005.92	***79,940.44***	*11.42*	***14.04***
Biogas refining	646,963.68	-		-		*0.00*	
Option 2: Electricity & Heat							
AD1							
Elect. consumption	28,081.34	15.14	43.41	28,139.89		*140.17*	
CH_4 leakages	-	12,264.00	-	12,264.00	***41,327.22***	*61.09*	***205.86***
Combustion CHP	116,362.00	-	923.34	923.34		*4.60*	
AD2							
Elect. consumption	14,903.44	8.03	23.04	14,934.52		*2.62*	
CH_4 leakages	-	65,005.92	-	65,005.92	***86,494.28***	*11.42*	***15.19***
Combustion CHP	825,937.48	-	6,553.84	6,553.84		*1.15*	

Note: Numbers in grey represent the GHG emissions considered neutral since the carbon emitted is biogenic and comes from plant residues.

Table 18: Saved CO_{2eq} emissions from energy production

	CO_2	***CO_{2eq} from CH_4***	***CO_2 Eq. from N_2O***	***TOTAL CO_{2eq}***	
		kg/year		kg/year	kg/tonne OFMSW
AD1					
Option 1	-	717,444.00	-	*717,444.00*	***3,573.82***
Option 2	37,411.44	20.17	57.83	*37,489.44*	***186.75***
AD2					
Option 1	-	3,972,528.00	-	*3,972,528.00*	***697.67***
Option 2	262,566.34	141.54	405.89	*263,113.76*	***46.21***

Table 19: Overall GHG saving potential and CO_{2eq} saving ratio

	CO_{2eq} Emitted		***CO_{2eq} Saved***		***CO_{2eq} Saving potential***		***CO_{2eq} Saving Ratio***
	kg/year	kg/tonne OFMSW	kg/year	kg/tonne OFMSW	kg/year	kg/tonne OFMSW	
AD1							
Option 1	40,403.89	201.26	717,444.00	3,573.82	677,040.11	***3,372.55***	**6%**
Option 2	41,327.22	205.86	37,411.44	186.75	- 3,837.79	***-19.12***	**110%**
AD2							
Option 1	79,940.44	14.04	3,972,528.00	697.67	3,892,587.56	***683.63***	**2%**
Option 2	86,494.28	15.19	263,113.76	46.21	176,619.48	***31.02***	**33%**

4.3.3.1 Direct CO_{2eq} emissions due to electricity consumption

As observed in Table 18*:* Saved CO_{2eq} emissions from energy production, the total project CO_{2eq} emissions were calculated resulting from the sum of the electricity consumption, methane uncontrolled losses, and energy production. The emitted CO_2 by the biogas refining processes was considered neutral due to their biogenic origin. For the first option of biomethane production, results show that with the current rates of OFMSW treated (AD1 = 0.55 and AD2=15.6 tonne per day), the CO_{2eq} emissions per year of AD2 are coherently superior to AD1, releasing about 39,536 kg of CO_{2eq} more than AD1 yearly. Nevertheless, when it comes to their direct efficiency per treated tonne of OFMSW, it can be realized that AD2 emits far fewer GHG´s. With 14 kg CO_{2eq}/tonne OFMSW for AD2 and 201 kg CO_{2eq}/tonne OFMSW for AD1, the dry system emits only around 7% (or 14.3 times less) of the total emitted by the wet AD system.

Similar results are presented for the second option of electricity and heat production, which includes the GHG´s emitted by the combustion in the CHP plant, where AD2 releases 7.3% of the total GHG releases of AD1 (12.9 times less). 15.19 and 205.86 kg/tonne OFMSW, respectively.

It can be deduced that these results are due to the vast amounts of electricity consumed to operate the wet system (as presented in section 4.3.2.4) and with this, the need to combust fossil fuels releasing ultimately considerably large quantities of GHG. The CO_2 emitted by the Combustion processes was also considered neutral, as shown in Table 18*:* Saved CO_{2eq} emissions from energy production.

4.3.3.2 Saved CO_{2eq} emissions due to energy production

Here, the CO_{2eq} emissions saved from biomethane production were calculated as the first option or secondly electricity and heat. As can be deduced, since AD2 treats more organic waste daily, it can save much more emissions than AD1. Biomethane production could potentially reach around 3,255,084 CO_{2eq}, more savings than AD1 if biogas is converted to biomethane. However, the output of AD1 becomes much more efficient when it comes to a direct saving per treated tonne of OFMSW. AD1 can save up to 3,573.82 CO_{2eq} kg, while AD2 around 697.67 kg CO_{2eq}/tonne OFMSW. These results show 5.12 times more savings for the AD1; or AD2 can save 19.5% of the total saved by AD1. These results demonstrate the efficiency of wet systems when it comes to GHG emissions mitigation, considering their more effective biogas and biomethane production rates.

For the second option (electricity and heat production), the results considering the projected CHP combustion system (non-existing) of AD1 (production of 200 kWh of electricity per day) show again the efficiency of AD1 with a total CO_{2eq} saving potential of 186.75 kg/tonne OFMSW, which is more than four times more direct savings that the 46.21 kg/tonne OFMSW of AD2.

CiBiogas could carry out further investigation to determine the actual electricity and heat generation potential. However, up to now, as stated by their specialists in the questionnaire Annex B and C, this plant satisfactorily converts biogas to biomethane to supply its fleet.

4.3.3.3 The overall GHG saving potential and CO_2 savings ratio.

Ultimately, the CO_{2eq} saving potential was calculated together with the CO_2 saving ratio to determine the direct GHG mitigation efficiency for the presented scenarios. The results show that AD2 can save much more GHG than what it emits, reaching a saving potential of 3,892,587.56 kg CO_{2eq} (Carbon dioxide equivalent) yearly, and the AD1 can reach a saving potential of 677,040.11 kg CO_{2eq} annually when biomethane is produced.

These results can be drawn even when the GHG´s emissions represent a more significant portion of the savings in AD1 than in the AD2 case, which was determined by the CO_{2eq} savings ratio. In other words, for AD1, 6% of the total CO_{2eq} Saved is emitted via electricity consumption and CH_4 losses. For the AD2, only 2%. These results also show the effectiveness of the dry system, demonstrating that it can save much more emissions than what it emits.

AD2 efficiency is also seen for the option two on the generation of electricity and heat. For this treatment plant the current scenario and including heat production shows that around an overall of 176,619.48 kg CO_{2eq} could be saved from being released to the air every year. This is equal to 31.02 kg of CO_{2eq} for every treated tonne of OFMSW; the GHG emitted is approximately 33% of the total emissions saved.

Nevertheless, in the case of AD1, considering a suggested CHP production unit of 200 kWh of electricity and 363.64 kWh of heat per day, results show that the plant would emit more GHG´s (205.86 kg CO_{2eq}/tonne OFMSW) than what it can actually save (186.75 kg CO_{2eq}/tonne OFMSW). This is attributed to its high energy consumption and methane leakages and losses of 1%. Thus, considering the large amounts of electricity consumption (700 kWh/day), in order to maintain at least neutral the CO_{2eq} savings and emissions, methane uncontrolled losses have to be kept below .69% of the total biogas produced; or as an alternative option, a larger CHP system might be implemented.

4.4 Key findings

This research phase studied two existing biodigestion plants in Brazil as case studies to determine their pros and cons regarding their effects in water savings, waste management, nutrient, and energy generation. Also, their GHG mitigation potential delimited by their system boundaries was analyzed. Pairwise, as one operates under dry digestion and the other as a wet digestion system, the intention was to compare their performance through a multicriteria analysis and resolve the more efficient performance for each study area.

Firstly, regarding water and leachate emission and savings, the results demonstrate that the dry system utilizes less water through its processes, as one of its main advantages. At the same time, the water needs of WAD systems do not represent large amounts, and the resulted liquids can be utilized to fertirigate the crops or plantations around the site.

Another resulting advantage for the DAD system is that it produces almost 2.5 more solid digestate or biofertilizer, with roughly 233 kg/tonne OFMSW compared to the 100 kg/tonne OFMSW the WAD plant. It also tolerates impurities content, resulting in a more robust system; however, source segregation is recommended and tolerate up to 10% of impurities or inert wastes. The removal of aggregates as a pretreatment step for both systems shall help produce more outstanding biosolids after the methanization process. In WAD, the resulted Liquid fertilizer, accounts for 74% of the emitted substances (740 L/tonne OFMSW). In DAD, roughly only 1.5% (232 L/day OFMSW) of the outputs are used as fertigation liquid. Approximately 2,215 L/day are discarded.

On the other hand, the WAD system accounts for a greater energy generation rate per unit tonne of treated OFMSW. It produces 5.28 times more biogas than the dry digester; 290.91 m^3 per tonne OFMSW for the AD1 compared to just 55 m^3/tonne OFMSW of the AD2. Thus, this resulted in the potential production of 170.18 m^3 of biomethane for the WAD system, in contrast to the 33.68 m^3 for DAD, for each tonne of collected and treated OFMSW.

Nevertheless, according to this analysis, results demonstrate that even with the significant biogas production performance potential of AD1, the disadvantage of AD1 comes when the energy consumption by the plant is considered. In this plant, a total of 700 kWh are supplied every day (1,273 kWh/tonne OFMSW) by Itaipu Binational to maintain the plant running, mainly due to pumping and mixing systems demand considerable amounts of electricity. Consequently, even when AD1 is much smaller it consumes more energy than AD2.

As for what electric and thermal energy concerns, AD2 has an installed cogeneration CHP system with a capacity of up to 35 KW of electrical energy, produces approximately 91 kWh per tonne of OFMSW, and results in a production of 1,419 kWh of electricity per day. This energy is sufficient to supply the daily demanded 374 kWh of electricity and end up every day with an approximate surplus of 1,045 kWh. This energy could also supply some of the energy demand of the Caju´s treatment plant or injected into the power grid. The plant can also potentially generate 6,433.3 kWh/day of thermal energy; equivalent to 412.4 kWh/tonne of OFMSW.

As for AD1, electricity and heat generation is just seen as a possible future option. The managers foresee installing a generator to produce approximately 200 kWh/day, equivalent to 363.64 kWh per tonne of treated OFMSW. As for the thermal energy production in order to be comparable, this study assumed the same efficiency value of the CHP installed in the AD2, producing heat and electricity in a rate of 4.5:1, respectively; resulting in a production of around 900 kWh/day of thermal energy; equivalent to 1,648 kWh/tonne of OFMSW.

Thermal energy is not produced in either of the plants; however, there is a detected factual potential for this energy resource to potentially supply heat to the treatment plants and be utilized to dry and sanitize the digested material (MD) and internal heating of the biodigesters.

These results disclose the energy efficiency of the AD2 system, even though it produces less biogas than AD1. The energy efficiency is represented by the energy ratio, which shows that for the AD2, 26.4 % of the energy contained in the biogas produced is utilized for the internal usage of the plant. Whereas for AD1, the energy consumed represents approximately 68% of the total energy produced. This is attributed to the fact that AD1 demands large amounts of energy for its pumps and mixing systems operations.

It is relevant to mention that this efficiency could be further improved utilizing its overall energy potential either converting biogas to biomethane (Option 1) or utilizing the thermal energy (Option 2) resulted from the CHP system;

For the Option 1 of biomethane production, the AD2 plant could reach a production of 345.5 kWh/tonne OFMSW resulting in an ER of 6.4%. However, in case biomethane is produced in this plant there would be an extra consumption of energy, which is unknown and not considered in this study. In the case of AD1, the plant already consumes around 68% of the total energy produced.

The Option 2 of electricity and thermal energy production in the CHP unit also shows the efficiency of AD2 considering that in the case that the plant utilizes also its thermal energy produced; the consumption of energy within the plant would represent only around 4.8% of the total energy production (374 kWh/day electricity consumption & 1,419.6 kWh/day of electricity generation and 6,433.3 kWh/day of heat generation). On the other hand, in the case a CHP unit (with similar characteristics) was implemented in AD1, still the plant would consume 63% of all the energy it would produce (700 kWh/day electricity consumption & 200 kWh/day of electricity generation and 906 kWh/day of heat generation).

Both treatment plants present opportunity areas for their improvement. They are climbing up on their learning curve, and new practices and technologies could be implemented to produce more energy with the less possible resources.

Regarding GHG mitigation potential, results demonstrate the efficiency of wet systems, considering their significant biogas production rates. For Option 1, AD1 can save up to 3,573.82 kg CO_{2eq}/tonne OFMSW, while AD2 around 697.67 kg CO_{2eq}/tonne OFMSW; this is 5.12 times more. However, when it comes to the plant's direct emissions due to its electricity consumption and CH_4 leakages per treated tonne of OFMSW, AD2 emits far fewer GHG´s. With 14 kg CO_{2eq}/tonne OFMSW for AD2 and 201 kg CO_{2eq}/tonne OFMSW for AD1, the dry system emits only around 7% (or 14.3 times less) of the total emitted by the wet AD system.

Combining these values, the results show that AD2 has a more significant GHG mitigation potential saving much more GHG than what it emits. It reaches a yearly saving potential of 3,892,587.56 kg CO_{2eq}. The AD1 can reach a saving potential of 677,040.11 kg CO_{2eq} yearly when biomethane is produced. However, when the amount of OFMSW daily treated is considered, results demonstrate the efficiency of the wet system reaching a saving potential of 3,372.55 kg/tonne OFMSW. This GHG saving potential of the WAD system is 4.9 times more than the 683.63 kg/tonne OFMSW that the dry system can ultimately save if a biomethane generation system is installed in this plant. Furthermore, the CO_{2eq} savings ratio was determined, which demonstrated that for AD1, 6% of the total CO_{2eq} saved are emitted via electricity consumption and CH_4 losses. For the AD2, an estimated 2% of the total CO_{2eq} potentially saved would be emitted, if biomethane was also produced.

For the Option 2, with the current CHP scenario of electricity generation and including heat generation in AD2 results show that of the GHG emitted would be approximately 33% of the total emissions potentially saved. In the case of AD1, considering a suggested CHP production unit of 200 kWh of electricity and 363.64 kWh of heat per day, results show that the plant would emit more GHG´s (205.86 kg CO_{2eq}/tonne OFMSW) than what it can actually save (186.75 kg CO_{2eq}/tonne OFMSW). This is attributed to its high energy consumption and supposed methane leakages and losses of 1%.

These results show the effectiveness of the dry systems for GHG mitigation, demonstrating that it can save more emissions than what it emits, if the plant produces either biomethane or electricity and heat.

5 A POLICY FRAMEWORK FOR THE IMPLEMENTATION OF ANAEROBIC DIGESTION

This phase carries out an objective document analysis of the current governmental policies, regulations, and governmental actions regarding treating the OFMSW through anaerobic digestion technologies. The purpose is to attend the third objective of the research, together with a series of interviews and questionnaires to key actors, researchers, and public policy specialists. The aim is to identify the limitations, challenges, and opportunities to apply AD from a governmental perspective. With this, recommend and propose the political guidelines and actions to implement large-scale AD projects to treat the OFMSW, specifying DAD technologies. For this purpose, this phase uses a framework adapted from [292] and [293], which offers step-by-step guidance for policy analysis: (1) Introduction and research objectives; (2) Methods; (3) data collection; (4) data analysis and interpretation; and (5) policy proposal.

5.1 Introduction and research objectives

The imperative need to implement and disseminate biodigesters for the treatment of OFMSW arises from the environmental, social, and public health impacts caused by traditional practices of disposal of organic waste in dumps and sanitary landfills. These standard practices cause inefficient use of raw materials, energy, and urban areas.

In Brazil, 60% of the municipalities currently dispose of wastes in inappropriate places, mainly dumpsites or poorly managed landfills [294]. In Mexico, there are 238 sanitary landfills and 1,643 open dumps. In many of them, the disposal is inadequate and represents a risk to the population's health and the environment [295]. On the other hand, in both countries, hundreds of medium and large-scale biodigesters have been installed so far to treat various substrates and organic effluents. However, the vast majority are in the rural sector, and there are few cases in which OFMSW is successfully processed by this method [296][297].

In Brazil, 79 million tonnes of MSW were generated in 2018 [298]. In Mexico, in 2019, over 44 million tonnes of this waste were generated [295]. Of the total, the organic fraction reaches over 50% in both cases [299][300]. With this, great potential is envisaged for its adequate treatment and production of bioenergy.

Research objectives

This qualitative research and policy assessment has the following objectives:

1. Track and describe the past and current state of public policies regarding organic waste treatment and biogas in Brazil and Mexico;
2. Description and discussion of the current situation and policies that influence DAD systems;
3. Detect and define the problems for the lack or poor implementation of DAD systems;
4. Detect and define the diverse challenges and opportunities for the implementation; and,
5. Determine policy guidelines and recommendations.

5.2 Methodology

5.2.1 Data collection, organization, and analysis

The data collection for this phase includes primary and secondary information. It comprises Interviews and questionnaires as helpful research tools, document and archival data, and firsthand data information obtained from conferences and online forums.

The strategy implemented for collecting all data was based on the theoretical sampling method, a data compilation method based on concepts derived from data. The purpose was to collect data from specific places and stakeholders to maximize the opportunities to develop new concepts and identify the relationships between the data obtained [301].

Based on the grounded theory, the theoretical sampling method was selected for this study because it is an open, flexible, and practical collection system, which enables to follow the research according to the areas that best serve the developing theory. It also presents the attribute to readapt the research tools according to data acquisition throughout the collection stage. This peculiarity of the method served considerably in this research to readapt the questions according to the analysis of the first data collected, which helped to look for the best source of data, find the answers for the questions and learn more about the concepts developed. Theoretical sampling also allowed to explore the diverse studied topics and issues from various angles with an open perspective.

The procedure of the theoretical sampling followed an analytic trial. A list of primary questions was developed mainly targeting to accomplish the objective 3 of the research. The questionnaire was thoroughly revised and readapted several times to build a final two sets of questions for each country. During the development of the interviews and questionnaires and a pre-analysis of the obtained information, it became more evident what specific data needed to be collected to focus on. Furthermore, interviews and questionnaires were carried out to the point that each topic demonstrated density and was well developed in terms of their properties and dimensions and add variation, reaching a level of data saturation, as suggested by Corbin & Strauss (2015) [301]. The author describes that this stage is achieved “when no new categories or relevant themes are emerging”; and various properties and dimensions of each category were identified. Reaching this point, the theory and data obtained was dense and logical enough that there were no gaps in the explanations. It was determined that at least three specialists have the same or similar responses to a specific question for each asseveration stated in the results chapter. Otherwise, each answer described here was referenced to each respective interviewee. The results from the questionnaires were complemented in many cases with literature references to give robustness and strength to the statements. If a question´s answer had no relation to the topic or did not fill the knowledge gaps, it was not included in the results and became part of the study's limitations.

5.2.2 Literature and policy review

In this research step, the case study of Brazil and Mexico is presented based on the analysis of the current state of their respective legal frameworks concerning the treatment of the OFMSW through AD technologies. The study systematizes public policies and regulations that have fostered AD implementation in both countries.

The plan was to collect secondary information – mainly existing public policies and regulations – from diverse national and international entities, present a deep analysis of the policy instruments, and evaluate their potential changes and improvements. Sources such as governmental and non-governmental organizations, public and online libraries, and websites were revised to obtain all possible secondary data related to organic waste and anaerobic digestion policies and regulations in Brazil and Mexico.

Furthermore, this process required a structural analysis to classify and organize the available information in the field, i.e.: (1) Public policies on the management and treatment of the OFMSW through AD technologies; (2) Policies on bioenergy and biofuels; (3) Other complementary laws, strategies, and decrees. For that matter, this data analysis adopts the "Archive Research Method" with the following steps:

1. *Defining source and unit of analysis*: The review has included the legislative framework, regulations, government strategies, and programs regarding the treatment of the OFMSW through AD technologies; all these are found in scientific databases, governmental and non-governmental organizations, educational and renowned institutions related to the topic of interest. The search for the documents other than policies and governmental regulations used the following keywords: policy OR politic* OR regulat*; AND “anaerobic digestion” OR biogas; AND Brazil OR Mexico.

2. *Sampling*: Policies and secondary information of various national and international entities were compiled, resulting in the archival of multiple laws and documents.

3. *Filtering and assembly of evidence*: Once the first sample of documents and files was defined, they were filtered according to their relevance to the subject. Hence, just the data associated with the project objectives were valid for this purpose from all the data collected. The data selected shall be that one which could be turned into information and evidence and attend three principal aims: 1) to assess the nature and extent of the problems; 2) to assess the historical and current state of anaerobic digestion, and 3) to assess policies that have been proposed in situations like the one in question.

4. *Information analysis*: An analysis of the information obtained was carried out to define the relevant policies, the reasons for the lack or the poor implementation of AD systems in both countries, and their potentialities for their implementation and dissemination.

5.2.3 Interviews and questionnaires

This research phase includes primary data findings from various semi-structured interviews, carried out between February 2020 until May 2021, incorporating various specialists such as local stakeholders, consultants, researchers, and policymakers in Brazil and Mexico. Thus, the Institutions and specialists selected for each interview, hereafter mentioned, must have active involvement in research, management, policy, and decision making in the area of anaerobic digestion, waste treatment, and bioenergy. This selection of specialist had the purpose to understand the most specialized, relevant, and diverse perspectives of the state of the art of OW treatment through AD and thus document the highlights of the current scientific and political trends on the topic.

The purpose was to develop and present a particular questionnaire to the specialists with a semi-structured nature, where questions allowed for improvisation and more substantial answers. For this purpose, there were two types of questionnaires for each country. One focused on more general and technical aspects, which were addressed mainly to researchers and specialists. A second one is related to the political and governmental aspects of policy specialists. The standardized questionnaires can be revised in the Appendices section.

The semi-structured nature of these questionnaires allowed omitting or adding questions during the process, depending on the specific situations. Due to the current pandemic situation, it became difficult to realize face-to-face interviews; therefore, the interviews were carried out either via videoconference; or the questionnaire answered directly by the specialist in a written form as a Word document; this was decided according to the preference of the interviewees. All the responses were captured in written form. Most of the video calls were recorded. The responses that ignored the topic or preferred to reserve their opinion were not considered in the presentation and analyses of the results. Additionally, secondary information was registered from online forums, podcasts, and conferences; extensive notes were taken, reviewed, and verified to register them.

For Brazil, the consulted researchers, specialists, and policy specialists were from the following Institutions: Altereko sas; & International Solis Waste Association (ISWA); Brazilian Association of Biogas and Biomethane (ABiogas); Brazilian Association of Energy Recovery of Waste (ABREN – WtERT); Energy Research Office (EPE); Environmental Company of the State of São Paulo (CETESB); Institute of Energy and Environment/ The University of São Paulo (IEE/USP); International Center on Renewable Energy/Biogas (CIBiogas); Network of Biodigesters for Latin America and the Caribbean (RedBioLAC); Paraná State Secretariat for the Environment and Water Resources; Sanitation and Energy Regulatory Agency of the State of São Paulo (ARSESP); United Nations Organizations for Industrial Development (UNIDO).

As for the Mexican case, the interviewees are from: Experts in Solid Waste Management (ECOTEC); former member of the Secretary of Energy; ELNSYST, S.A. DE C.V. (IBTech®): Faculty of Engineering - Autonomous University of the State of Mexico / Mexican bioenergy network, A.C. (REMBIO); Gaseous Biofuels Cluster (CEMIE-BIO); Institute of the Americas; Metropolitan Autonomous University (UAM); Mexican Association of Biomass and Biogas (AMBB); Mexican Oil Institute (IMP); National School of Biological Sciences (ENCB) of the Polytechnic National Institute (IPN); National Chamber of the Energy Industry (PROCNIE A.C.); National Council of Biogas A.C. (CNBiogas); Potosino Institute of Scientific and Technological Research A.C. (IPICYT). Additionally, some of the interviewed specialists had experience in Organizations such as the Secretary of Energy (SENER); Secretary of Environment and Natural Resources (SEMARNAT).

Throughout this investigation, we also tried to contact and interview other relevant organizations, dependencies, and institutions specialists in the field; however, we either did not receive a reply from them or did not show interest in the purpose of this research. For the Brazilian case, these were: Ministry of Mines and Energy (MME); National Agency for Petroleum, Natural Gas and Biofuels (ANP); São Paulo State Sanitation and Energy Regulatory Agency (ARSESP); Brazilian Association of Public Cleaning and

Special Waste Companies (Abrelpe); Brazilian Association of Waste Treatment Companies (Abetre); Brazilian Association of Infrastructure and Basic Industries (Abdib); Methanum Waste and Energy; and the Ministry of Science, Technology, Innovations and Communications (MCTIC). For the Mexican case, the following Institutions did not participate in this research: Energy Regulatory Committee (CRE), German Cooperation for Sustainable Development in Mexico (GIZ), and the Mexican Center for Environmental Law (CEMDA).

The objectivity of the interviews and questionnaires

Questionnaires and interviews are effective methods of data collection from research participants. A strength of the interviews is that it allows to freely use probes to obtain more clarity on the responses or additional information [302]. As this author suggests, qualitative interviews were carried out, which intended to get in-depth information about a participant´s thoughts, beliefs, knowledge, reasoning, motivations, and feelings about the diverse topics of this study.

Any proficient policy analysis should be “objective” and not “political” [303]. Thus, the purpose of the interviews and questionnaires study was to identify the best solution or proposal for each case, identify the possible options, and search for repetition on the answers to give them for sure.

In case that the answers to each question differ from one another, to provide an objective and value-free analysis, the results are presented, attempting to identify the best option weighing up their pros and cons with an interpretative orientation. The presentation of the results references the authors that mentioned each statement.

Thus, this research attempted to reach validity on the results´ conclusion by searching for “triangulation” as an outcome, which occurs when the results attain the same conclusion, trying to avoid any research bias. Triangulation is a validation approach based on the convergence of multiple investigations, methods, data sources, and theoretical perspectives. Also, looking for interpretive validity refers to portraying the interviewees´ views on each topic [302].

5.2.3.1 Data organization and analysis

These interviews & questionnaires provided qualitative data as a general sense of the vast knowledge on AD technologies and waste management at multiple levels. For this purpose, the Grounded Theory (GT) was implemented in the analysis to access subjective preferences of stakeholders and objective and subjective performances of OFMSW treatment options. GT is a type of qualitative research and is the strategy implemented to identify the critical elements of the collected information and then categorize the relationships of those elements to the context and process of the research to construct theory grounded in data. Theoretical sampling was the method used for the data collection, as described in section 5.2.1.

Once the collection of the data was carried out, the procedure for the development and analysis was as follows:

1. *Coding:* Develop categories that involve the same field of study. For the technical questionnaires, these categories are: (i) Waste Management Generalities; (ii) Dry anaerobic digestion technical aspects; (iii) economic factors; and (iv) policy aspects. For the questionnaires to policy specialists: (i) Antecedents and current policies; (ii) Social contributions; (iii) Environment and sustainable use of natural resources; (iv) Energy market; and (v) Other recommendations.
2. *Develop a list of concepts and subcategories:* The categories were then sorted into subcategories derived from the correlation of the data obtained. These categories are shown in the following tables:

Questionnaire to Researchers	
Waste Management Generalities	***Economic factors***
1. Landfilling, composting & anaerobic digestion	*9. Future financial viability*
2. Source segregation systems	*10. Development of national technologies*
3. Feasibility of wet and/or dry biodigesters	***Policy aspects***
4. AD Technologies to treat OSW	*11. Previous public policies and regulations*
DAD Technical aspects	*12. Flaws of the current legislation related to AD systems*
5. Reasons and challenges to implementing DAD systems	*13. Current policies contribution*
6. Challenges to implement DAD systems	*14. Recommendations to foster AD technologies*
7. Less water utilization in DAD systems	
8. GHG reduction goals	

Questionnaire to public policy specialist in Brazil	***Questionnaire to public policy specialist in Mexico***
Current policies	***Antecedents and current policies***
1. Low carbon energy systems	*1. Previous initiatives and attempts to install biogas projects*
2. Current regulations: RenovaBio, PNRS, PNE, & PDE	*2. Clean Thermal Energy Certificates (CETEL)*
3. Other political instruments, new laws, or regulations	*3. Current laws and regulations*
Social contributions	***Social contributions***
4. Social benefits and participation	*5. Social benefits and participation*
Environment and sustainable use of natural resources	***Environment and sustainable use of natural resources***
5. Mitigate environmental degradation	*6. Mitigate the possible environmental degradation*
Energy market	***Energy markets***
6. Opportunities and barriers of biogas markets in Brazil	*7. New financial incentives for the creation of biogas projects*
7. Biomethane vs. biodiesel, diesel, gasoline, and ethanol	*8. Biomethane vs. biodiesel, diesel, gasoline, and ethanol*

3. *Analysis of findings and interpretation:* Once the dataset was carefully selected and categorized, the next step was a detailed analysis to revise the interviews and questionnaires to cross-analyze the relevant data obtained. The primary purpose was to relate the data obtained from the diverse respondents, detect the highlights, summarize the findings according to each category, and develop the body of work. The obtained information was complemented with primary and secondary data obtained from the literature revision, conferences, and forums online presented by some of the main actors in the biogas field of both countries.

4. *Policy proposal:* The research defined the problematics, challenges, and reasons for the lack or poor implementation of DAD systems in both countries. Hence, after recognizing these issues and challenges, the research focused on searching for patterns to detect the real chances and opportunities for AD, particularly DAD technologies. Finally, recommendations were drawn for the guidelines and political actions to foster these technologies from then on.
5. *Next steps and conclusions:* Finally, conclusions were drawn attempting to state the actual chances that AD and specifically DAD technologies have in both countries and propose the following steps to achieve this goal.

5.3 Literature Review: Past and current state of public policies in Brazil and Mexico

In Brazil and Mexico, the treatment of OFMSW using biodigesters already had its first manifestations in the respective legislative frameworks, with the enactment of various laws and government plans that encourage the implementation of these technologies. There are currently several efforts and initiatives to create new national regulations because legal, financial, operational, and management gaps inhibit the adequate treatment of OFMSW at a significant rate. Sanitary landfills and dumpsites are the most common practice to dispose of these residues.

In both countries, a legislative framework, programs, and strategies have been developed to address the treatment of OFMSW through biodigesters and the production of biofuels. This research presents a synthesis of these policies and the analysis to determine the potential for the adequate implementation of biodigesters.

5.3.1 Policies on the management of the Organic Fraction of Municipal Solid Waste

In Brazil, following the National Solid Waste Policy, Law 12.305 (Brazil, 2010), enacted in 2010, only materials that do not have technical and economic viability should be destined to landfills. These wastes clearly do not include the organic fraction (among the various recyclable materials); thus, avoiding its loss and promoting the reduction of the social and environmental impacts associated with its inappropriate disposal. At the same time, within the objectives of this policy are the adoption, development, and incentives to use systems and technologies for the utilization of solid wastes, including their recovery and energy use.

However, this policy places little emphasis on the implementation of biodigesters. It was not until months later, with the National Solid Waste Plan (PNRS), Decree 7.404 (Brazil, 2010), when a guideline was generated for the energy use and recuperation of the OFMSW through biodigesters, as well as from composting processes. The use of the resulting digestate as an organic compound for agricultural purposes is also mentioned. In this PNRS, a strategy is also created to provide financial resources and tax reduction incentives to implement new composting units, sanitary landfills, and biodigesters. A strategy is also designed for beginning carrying out social awareness activities to properly segregate waste at its source and disseminate knowledge about biodigestion and biogas production.

In addition to these policies, concerning the adequate treatment of waste and sanitation, there is also the National Basic Sanitation Plan (PLANSAB), Decree 8.141 (Brazil, 2013), which establishes the strategies for the management of essential sanitation services, promoting the improvement of efficient sanitary systems through the energy use of biogas. It proposes to expand the selective collection, recycling, and energy use of the OFMSW, establishing as a goal the treatment of 2.8% of this waste through composting or DA and 10.4% until 2033. This aim also shall meet the goals for reducing greenhouse gas emissions.

In the case of Mexico, federal legislation, and that of some states (State of Mexico, Nuevo León, Puebla, and some municipalities) propose adequate waste management techniques. In the General Law for the Prevention and Integral Management of Solid Waste (México, 2018) organic and inorganic waste is classified to facilitate their segregation and disposal in sanitary landfills or controlled dumpsites. This law specifies that the Mexican normative shall establish the conditions that the facilities must meet, and the types of waste disposed of in them. It also demonstrates in which cases the biogas generated was used.

In line with this, the General Law on Climate Change (México, 2018) promotes the energy potential contained in waste to mitigate greenhouse gases through the integral management of waste and energy generation. With this, it stipulates the reduction of emissions in the waste sector through the development, construction, and installation of adequate infrastructure, call it biodigesters, in urban centers with more than fifty thousand inhabitants, also minimizing and valuing urban solid waste. Accordingly, more specific actions are considered in the National Climate Change Strategy (México, 2015) which encourages the participation of the private sector in projects of separation, reuse, waste recycling, and the development of biogas plants for the integral management of solid waste.

One issue identified in waste management in Mexico is that currently, there is no charge, or minimum fees, for the disposal of the organic fraction in dumps or sanitary landfills. This limited taxation system represents difficulties by not collecting contributions, which could help implement programs and technologies for proper treatment. In addition to this, another major problem is the lack of an efficient organization in several of the unions of garbage pickers (informal collectors) and cleaning workers since many times obstacles arise to automate or improve MSW management systems.

5.3.2 Policies on bioenergy and biofuels

The development of political actions towards the implementation of biogas and biomethane to optimize the energy sector is set according to the Ministry of Mining and Energy with a vision of long, medium, and short term [304], described in in the Forum “Panorama of Biogas in Brazil” as follows:

The National Energy Plan 2050, PNE 205 (Brazil, 2020) brings a vision of the next 30 years as a long-term policy. Based mainly on two aspects: 1) Strategic guidelines for where Brazil is going energy-wise, and 2) To transform these guidelines into more tangible things, with recommendations for government agencies to act.

The Ten-year Energy Expansion Plan “PDE” 2029 (Brazil, 2020) was derived from the PNE 2050 and was released for up to 2030, where action programs and new policies for biogas projects are becoming a reality. Accordingly, for implementing biogas and biomethane in the short term, there are mainly four opportunities: 1) new gas law; 2) RenovaBio program; 3) Increase in intermittent sources; 4) Green corridors. Further on described.

Long term: PNE 2050

The PNE 2050 is the regulation that develops the country's paths for the energy sector. It sets the government guidelines and strategy for the consolidation of the energy sector for the following years. Based on this document, it is determined what the policies considered by the various Institutes for implementing the national energy strategy are; monitoring and integrating new solutions for the market for energy use. It also evaluates the attributes of each energy source to trace the benefits that these can bring to the country.

The five guidelines derived from the PNE 2050 are:

1. Gradual replacement of petroleum products.
2. Creation and development of biotechnologies
3. Energy utilization of agricultural waste with the decentralized production of biogas and biomethane
4. Promote conditions for replacing diesel generation in isolated systems.
5. Efficient development of the natural gas market and infrastructure.

Biomethane stands out in these plans with a trend for the coming years.

Medium-term: PDE 2030

Derived from the PNE 2050 in 2017, the Ten-Year Energy Expansion Plan (PDE 2029) contemplated biogas in its electrical energy expansion objectives for the first time. This Plan reflects the energy use of biogas, considering that the most significant production of this is found in the use of agricultural residues, mainly from sugar cane, through the biodigestion of stillage and filter cake. In addition, it considers various other agro-industrial and urban substrates to be potentially used in the significant production of biogas.

In this plan, some conditions represent the potential expansion of biomethane in the energy matrix, for example, the expansion of agriculture, with an increase of 3.6% on the activities, the increase of the intensity of use of heavy load trucks, among others.

This plan also presents the mitigation measures from the federal government, such as:

1. Growth in the use of biofuels;
2. Expansion of renewable sources for electricity generation;
3. Increase in energy efficiency measures. Thus, according to the Ministry, biogas and biomethane play a fundamental role in this mitigation process.

Short term: New gas law; RenovaBio; Increase in intermittent sources; Green corridors

1) New gas law:

The new gas market law presents biogas and biomethane as equivalent to natural gas. It states that it may have equal treatment if it adheres to the specifications established by the ANP. It brings several opportunities to increase the supply of thermal energy and decrease the intensity of the carbon supply.

This law provides ventures for the insertion of biomethane such as 1) reduction of regulatory risk, 2) emerging solutions in strategic industrial sectors (fertilizers), 3) significant investments in infrastructure, 4) possibility of inserting biogas in REIDI (Special Incentive Scheme for Infrastructure Development).

2) RenovaBio

In 2017, the national RenovaBio Program, Law № 13.576 (Brazil, 2017) was instituted, which establishes annual national decarbonization goals for the biofuel sector, thus contributing to the fulfillment of Brazil's commitments in the Paris Agreement. This regulation encourages the increase in biofuels' participation in the country's energy matrix from 6% to 18% [305], specifically with bioethanol, biodiesel, and biogas.

The Program aims to develop a strategy to recognize the role of these types of biofuels both for energy security and for mitigating the reduction of greenhouse gas emissions [306]. The Program comprises three strategic axes: 1) Decarbonization Targets; 2) Biofuel Production Certification; and 3) Decarbonization Credit (CBIO) [307].

It also shows that biomethane has the highest energy efficiency score compared to other biofuels and the highest average volume eligible per biofuel. Even so, biomethane has very few certifications, because the ANP has registered few companies to produce biomethane. Furthermore, it is also understood that the Program could incorporate and encourage the use of biogas for motor vehicles by establishing progressive goals for the use of biogas with gas distributors in vehicles.

3) Increase in intermittent sources:

Biogas has the advantage of supplying the intermittency from wind and solar sources, together with the expectation of a higher proportion of self-production by renewables.

4) Green corridors:

Biomethane is an alternative to green corridors, thus contributing to renewable energy production in strategic areas.

Furthermore, another current initiative that is taking place to support the development of the biogas sector together with other renewable energies is the consortium BEP (Energy Program for Brazil). It is a program that focuses on regulatory innovations and market and technological policies in various renewable energy sectors, including energy recovery from waste and effluents. This energy program, funded by the UK government, unites Brazil and the United Kingdom to collaborate in implementing renewable energies and clean technologies [304].

In the case of Mexico, the Law for the Promotion and Development of Bioenergetics (Mexico, 2008) seeks to promote sustainable development and efficient use of bioenergetics. The dependencies: SAGARPA (now SADER), SENER, and SEMARNAT, formed the Bioenergetics Commission. It is established that these

Secretariats, together with the state governments, shall promote the creation of infrastructure to produce bioenergetics, creating incentives for the development of this Industry.

The Energy Transition Law (Mexico, 2015) encourages electricity production from bioenergetics, among other sustainable modes. Alternatively, the Law of Coordinated Regulatory Bodies in Energy Matters (Mexico, 2014) establishes that the National Energy Regulatory Commission shall regulate and promote the efficient development of transport, storage, and distribution of bioenergetics. Nevertheless, the current reform to the Electric Industry Law (2014) in March 2021 does not pay enough attention to bioenergetics and their contribution to the energy matrix in the country.

More recently, the national strategy called "Transition Strategy to Promote the Use of Cleaner Technologies and Fuels" (Mexico, 2020) emerged, which develops actions that affect the regulation and promotion of biogas technologies. It promotes the use and acquisition of bioenergetics in public sector companies and evaluates the establishment of financing programs and incentives to encourage the private sector for the energy use of MSW. Besides, this Strategy promotes the use of rural solid waste through biodigesters. Nevertheless, biogas is still not regulated in the country, which hinders its development; this is further discussed in section 5.4.3.

5.3.3 Other complementary laws, strategies, and decrees

In Brazil, some other ordinances and state regulations have been issued concerning the use and quality of biogas and biomethane. In the south-central region of the country, biogas is a widely used resource in the agro-industrial sector. States such as Goiás, Paraná, Rio de Janeiro, Rio Grande do Sul, Santa Catarina, and São Paulo have biogas and biomethane policies, which include the problem of MSW in their texts. For example, Decree No. 58,659 (Brazil, 2012) issued in São Paulo, regulates the percentage of biomethane in piped gas in the State and institutes the Paulist Biogas Program, which intends to include biogas in the state energy matrix permanently. Furthermore, Deliberation No. 744 (Brazil, 2017) establishes the conditions for distributing biomethane in the gas network in this State. The state of Ceará currently has the only treatment plant in the country that injects biomethane into the piped gas network, following the Decree No. 32600 (Brazil, 2018).

In addition, the national government decreed other laws. The ANP Resolution No. 8 (Brazil, 2015) specifies the quality of biomethane originated from agrosilvopastoral and commercial organic products and waste. The ANP Resolution No. 685 (Brazil, 2017) deals with biomethane quality control and specifications from landfills and wastewater treatment stations. Both resolutions include the requirements and regulations to inject biomethane into the natural gas network. Currently, the ANP is revising the proposal to unify both resolutions in a single norm [308].

More recently, the collaboration of several national and international Institutions has allowed the development of two new public calls to open biogas technologies to the local markets; one for tropicalization of technologies and another for consolidation of demonstrative units of biogas and biomethane [304].

Tropicalization program

As presented in the form for the launch of the Tropicalization Program / Global Environment Facility (GEF) [309], this technical program is linked to the “GEF project (Global Environment Facility) Biogas Brazil”, led by the Ministry of Science, Technology, and Innovations (MCTI). The United Nations Industrial Development Organization (UNIDO), financed by the Global Fund for the Environment (Global Environment Facility, or GEF), is currently implementing this Program.

The Tropicalization Program project aims to promote cooperation between Brazilian and foreign companies to identify opportunities that meet the demands of the local market. The Program's objective is to engage national and international stakeholders to encourage economic development and technological innovation aimed at the biogas value chain in Brazil.

GEF Biogas Brazil Project offers solutions to support companies and provide advice to local governments to develop public policies. It supports the integration between companies and financiers, creates new business models, free courses, strategic information, modernization of laws and policies, MSW management. The program's benefits are diversification of the energy matrix, mitigation of climate change and optimization of resources, implementation of national technologies, creating technological robustness.

Selection of biogas plants to become demonstration units

With this public call, existing biogas treatment plants are selected to receive direct support. The chosen plants will receive incremental investment and specialized support, incorporated into the GEF Biogas Brazil project as demonstration units (UDs).

The objective is to provide resources for investment in services, processes, and equipment to promote innovation and improvements in biogas plants within the scope of energy applications and the use of the digestate. These selected biogas plants will be linked to the GEF Biogas project as Demonstration Units.

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In Mexico, in 2014, because of an initiative from the Secretariat of Energy and the National Council of Science and Technology, the Mexican Centers for Energy Innovation (CEMIE) emerged. One of the objectives is the generation of bioenergy through DA technologies. Other complementary laws are:

- The recent Zero Waste Policy of SEMARNAT (México, 2019) [295], which encourages avoiding food waste and use the organic nutrients and energy potential of waste;
- NOM-083-SEMARNAT-2003 focuses on the management and disposal of residues in landfills, among other policies not directly relevant to the topic.

The NDC's goals of the Paris agreement also promote the biological treatment of OFMSW to reduce greenhouse gas emissions in both countries. Currently, there are other initiatives to prepare a new specific national normative for the regulation and use of biogas and biomethane in both countries.

Figure 20: Waste treatment plant in Foz do Iguaçu, Brazil. Source: CIBiogas files.

Figure 21: Waste treatment plant in Atlacomulco, México. Source: AMBB files.

5.4 Results and Discussions: Analysis of findings. Body of work from interviews

The following enlist the companies and institutions that took part in the interviews with specialists. Coded from TQBR01 to TQMX10, the interviews were carried out to researchers and technical specialists, and from PPQBR11 to PPQMX23, the interviews were dedicated to public policy specialists. This coding system helped to reference the results obtained from the interviews throughout the analysis of the information. The total given answers to the questionnaires by each interviewee can be found in the Appendices section.

Table 20: List of Companies and Institutes interviewed
Source: The authors

Code	Company/Institution		Job Position of the interviewee	Country	Location	Type of Questionnaire
RTQBR01	International Solis Waste Association; Italian Composting and Biogas Association; Altereko sas.	ISWA; CIC; Altereko	Chair of the WG on Biowaste (ISWA); Senior Expert (CIC)	Brazil	Verona, Italy	Researchers and technical Specialists
RTQBR02	Brazilian Association of Biogas and Biomethane	ABiogas	Technical Consultant	Brazil	São Paulo	
RTQBR03	Energy Research Office	EPE	Technical Consultant	Brazil	Rio de Janeiro	
RTQBR04	International Center on Renewable Energy/Biogas	CIBiogas	Director of Technological Development	Brazil	Foz do Iguaçu	
RTQBR05	Sanitation and Energy Regulatory Agency of the State of São Paulo	ARSESP	Specialist in Regulation and Inspection of Public Services	Brazil	São Paulo	
RTQMX06	Gaseous Biofuels Cluster	CEMIE-BIO	Leading Researcher	Mexico	Querétaro	
RTQMX07	Metropolitan Autonomous University	UAM	Professor and leading researcher	Mexico	Mexico City	
RTQMX08	Mexican Oil Institute	IMP	Specialist in Innovation and Technology Management	Mexico	Mexico City	
RTQMX09	National Council of Biogas A.C.	CNBiogas	Vice president	Mexico	Mexico City	
RTQMX10	Potosino Institute of Scientific and Technological Research A.C.	IPICYT	Senior Researcher "B" Environmental Sciences Division	Mexico	San Luis Potosi	
PPQBR11	Environmental Company of the State of São Paulo	CETESB	President	Brazil	São Paulo	Public Policy Specialists
PPQBR12	United Nations Organizations for Industrial Development	UNIDO	National Policy Specialist	Brazil	Brasilia	
PPQBR13	State Secretariat of Environment and Water Resources of Paraná	SEMA	Former Solid Waste coordinator; current Environmental Consultant	Brazil	Curitiba	
PPQBR14	Network of Biodigesters for Latin America and the Caribbean	RedBioLAC	Sustainability, Biogas and Energy Planning Specialist	Brazil	Foz do Iguaçu	
PPQBR15	Institute of Energy and Environment/ Bioenergy Research Group	IEE/USP (GBio)	Director of research group / Professor	Brazil	São Paulo	
PPQBR16	Brazilian Association of Energy Recovery of Waste	ABREN	Expert Member	Brazil	Brasilia	
PPQMX17	Mexican Association of Biomass and Biogas	AMBB	President and General Director	Mexico	Mexico City	
PPQMX18	Institute of the Americas	IOA	Non-resident Fellow & Board Member SEforALL	Mexico	La Jolla, USA	
PPQMX19	Experts in Solid Waste Management; Former member of the Secretary of Energy	ECOTEC/SENER	Projects Director /Former Bioenergetics Director at SENER	Mexico	Mexico City	
PPQMX20	ELNSYST, S.A. DE C.V.	IBTech®	Technical Director	Mexico	Toluca	
PPQMX21	Faculty of Engineering - UAEM / Mexican bioenergy network, A.C.	REMBIO	Professor and leading researcher	Mexico	Toluca	
PPQMX22	National School of Biological Sciences of the Polytechnic National Institute	ENCB/IPN	Professor and leading researcher	Mexico	Mexico City	
PPQMX23	National Chamber of the Energy Industry	PROCNIE A.C.	President of the Directing Council	Mexico	Mexico City	

5.4.1 Researchers and technical specialists in Brazil and Mexico

The arguments now presented resulted from the interviews with researchers and technical specialists from the following Institutions:

For Brazil: International Solis Waste Association (ISWA); Brazilian Association of Biogas and Biomethane (ABiogas); Energy Research Office (EPE); International Center on Renewable; Energy/Biogas (CIBiogas); Sanitation and Energy Regulatory Agency of the State of São Paulo (ARSESP).

For Mexico: Gaseous Biofuels Cluster (CEMIE-BIO); Metropolitan Autonomous University (UAM); Mexican Oil Institute (IMP); National Council of Biogas A.C. (CNBiogas); Potosino Institute of Scientific and Technological Research A.C. (IPICYT).

The following information represents the summary and integration of the perspective and opinions of the interviewees for each topic.

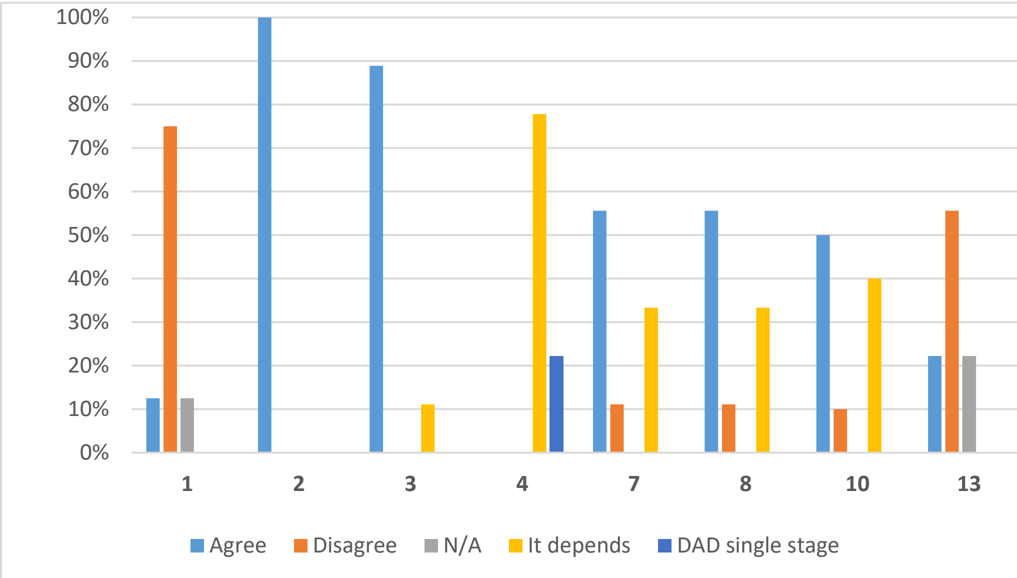
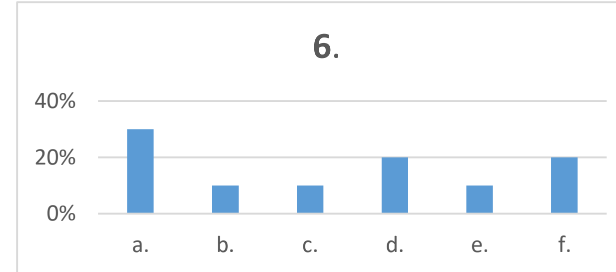


Figure 23: Percentage of answers agreeing or disagreeing with the questions´ argument

1. Should traditional OSW´s treatment means, such as landfilling and dumpsites, keep being implemented?
2. Could a waste source segregation system be implemented and thrive in the cities and towns?
3. Are traditional wet and dry biodigesters a feasible technology to treat OSW in these countries?
4. Which specific AD technology (from Figure 1) is the most appropriate to treat OSW residues?;
5. Why have DAD technologies not been transcendently implemented and promoted?
6. What are other challenges to implementing DAD systems?
7. Would less water utilization represent an advantage for DAD over WAD systems?
8. Can DAD technologies significantly contribute to reaching the countries' GHG reduction goals, according to the Nationally Determined Contributions (NDC´s) goals?
9. Could these technologies turn (or be more) financially viable in the future? What needs to be done?
10. Would developing AD biodigesters with local materials and technologies, specific for the country's conditions, contribute to DAD projects?
13. Are current policies significantly contributing to the implementation of AD projects?

a. Lack of technical knowledge
b. High operational costs
c. Poor substrate homogeneity and lack of mixture
d. Lack of public policy and governmental interest
e. Lack of compliance with the law
f. NA



a. Clear revenues from bioenergy and fertilizers
b. Disclosure its viability
c. Local producers of the technologies, national development
d. Increase its competitiveness
e. Include private sector to do business
f. Create economic incentives to encourage them.
g. Start campaigns for source segregation and clear revenues from bioenergy

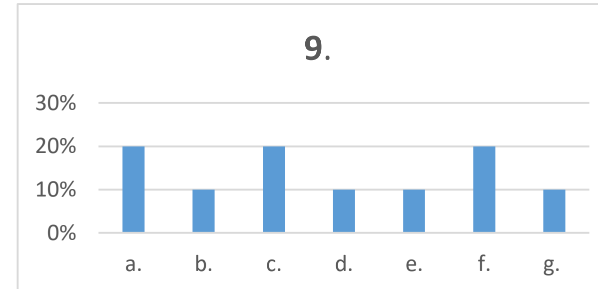


Figure 22: Percentage of answers received for each answer

Table 21. Reasons for the poor implementation of AD to treat OFMSW. Numbered in order of importance. (Number 1 = main reason); and/or "Na" if it does not apply, or no answer was obtained.

5.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
No financial viability/ high prices.	1	NA	1	3	3	5	2	4
Technical complexity	2	NA	3	6	5	6	3	NA
Lack of knowledge of the existence of these systems	NA	NA	2	2	4	3	1	2
Lack of interest of stakeholders. Which one:	NA	NA	NA	4,b.	2	2	6	5,e.
Public policy deficiencies	3	NA	NA	1	1	1	4	3
No concern of environmental issues	NA	NA	NA	5	6	4	5	1
Other(s)	--	a.	NA	NA	c.	d.	NA	NA

a. Recent development of vehicle utilization
b. Associated to the political situation
c. Lack of regulation to enforce law compliance.
d. Lack of investment interests; if there are significant financial risks, stakeholders disagree, and there is a lack of organization.
e. There are other sources available that are more attractive for the generation of renewable energy.

11. Why have previous public policies and regulations that have fostered the implementation of anaerobic digestion projects not continued and prevailed?

- Technology is complex; CAPEX is very high.
- They are linked to the destitution of gas (first carbon projects) or its use for electric energy
- Public policies have encouraged the implementation of biodigesters
- Landfilling is economically still the most competitive solution
- The misconception is that it is a process that does not work because of the poor implementation of digesters.
- In 2004 there was a boom in carbon credits, which encouraged biogas capture from landfills.
- Political will changes. Due to the political rotation at the municipal, state, and federal levels
- There are no governmental directives for their implementation.
- The competition with other renewables (wind and solar) are more attractive from an economic point of view.

12. What are the flaws of the current legislation related to AD systems? What is missing?

- Commitment from local authorities and economic sustainability of AD
- Lack of integration between sectors due to technological innovations
- More adequate investments are lacking for products of various sizes and high taxes on imported equipment in some states.
- Lack of surveillance regarding irregular disposal (dumpsites); secondly, landfilling is still the most ease and competitive solution; third, the lack of consciousness for source segregation
- The legislation does not comply. No one makes it happen
- The law for the management of urban solid waste should be better attended. Regulate the principles of circular economy in the existing laws.
- The responsibility to collect, dispose and treat waste should be of the states and not municipal.
- Poor focus on AD in the laws.
- More attention on AD technologies; wind and solar energy are considered the most attractive.

14. Could you propose recommendations or strategies on how to foster the implementation and dissemination of AD technologies, and more specifically, DAD projects;

- Expansion of DAD projects to the rural market
- Demonstrate the advantages of biodigestion for potential producers, especially of medium and large scale.
- Aim to avoid landfilling and foster the harnessing of material or energy waste content.
- Pilot plants to demonstrate that these technologies can be successful
- Encourage the participation of the private sector. Create incentives for private companies to be created.
- Share successful cases with decision-makers, instruct them, and have greater participation of specialists to advise them.
- Generate a report of the Anaerobic Digestion systems at the national and international level.
- Together with these, other general recommendations resulting from this set of interviews are included in section 5.4.1.5.

5.4.1.1 Waste management generalities

5.4.1.1.1 Landfilling, composting & anaerobic digestion

According to the Brazilian legislation, controlled dumps and landfills must be reduced, given their risk of contamination; only non-reusable garbage, i.e., waste that has no technical, environmental, and economic viability for reuse, must be sent to landfills. In Mexico, the regulation still recognizes the implementation of sanitary landfills as a viable option, establishing the conditions that the installations must have to dispose of the different types of residues.

In that sense, one of the questions to the interviewees was regarding their opinion on whether landfilling and dumpsites should keep being implemented and encouraged as waste treatment methods. For what 79% of the interviewees concord that it is a problem that needs to be addressed and these practices should be slowly reduced, limited, and banned; mainly dumpsites, which is a method that presents higher pollution and health risks, especially to the most vulnerable populations. These practices are also seen as unsustainable because they occupy large land extensions to process the wastes. Even when they produce biogas, revenues come many years later if there is, in fact, gas available by that time (*RTQMX07*).

As defined at the waste management hierarchy, supported by the United Nations Environmental Program, and used to guide most Waste Management policies worldwide, landfilling is the last resource that should be considered in waste management strategies. The hierarchy does not even consider dumpsites as waste management as it spreads diseases and pollutes watersheds and other water bodies (*RTQBR05*). Thus, it is a significant role of the Environmental Regulators to divert waste from dumpsites. When it comes to landfills, as it is the least valid treatment method, policymakers may set regulations to divert waste from them.

Some researchers (*RTQBR03* and *RTQBR05*) proposed that, as the Brazilian regulation mentions, only non-reusable garbage be sent to sanitary landfills to mitigate waste environmental impacts. Thus, there should be more space for new technologies that are more environmentally appropriate and bring benefits to communities and society (such as energy generation, carbon capture, job creation, among others). To achieve this, there was a proposal by one of the specialists (*RTQMX09*) to include “taxing sanctions”. These could be set for the disposal of organic waste in landfills, thus reducing the prevailing of these practices.

Furthermore, as pointed out by *RTQBR02,* one must understand and consider both countries´ social and economic diversity and, therefore, acknowledge that the change in waste management practices in a short period is unrealistic. It is a matter of changing the treatment means and implementing more effective actions in the non-generation, reuse, and source segregation of residues.

In Mexico, federal, many state, and municipal legislations provide adequate waste management (even intending to implement circular economies). However, as *PPQMX17* points out, one of the biggest challenges facing public policies is that most municipalities do not charge for waste disposal in landfills. Therefore, there is no money to invest in technologies, and when they charge (although there is a legal niche for them to do), the rates are meager, fluctuating between 40 to 120 pesos per tonne received. Another big challenge is formalizing garbage collectors and cleaning workers’ unions; the still informality of these workers is a bigger problem because it is usually one of the biggest obstacles to automatizing or improving the MSW management systems. In many cases, the municipalities want the concessionaires (when there are) to absorb the cost of liquidating the syndicates or workers' unions, which they do not do because it is expensive and a political cost. Therefore, the city majors keep tolerating garbage pickers, also called "pepenadores".

5.4.1.1.2 Source segregation systems

Most societies that produce and treat wastes in Brazil and Mexico misuse the residues and products generated, making it difficult to reuse them. Having a source segregation system, in theory, offers several advantages; however, there is still some public perception that this is not the case, together with other present challenges. A relevant one that must be taken into account is the fact that Brazil and Mexico are tropical countries. In many regions, their climates enhance the speed of decomposition of the organic matter; thus needing a more intense collection frequency.

Hence, another question to the interviewees was whether a waste source segregation system could be implemented and thrive in the cities and towns in Brazil and Mexico; and if this would represent an advantage for the treatment of OSW. All of them agreed; a source segregation system would firstly ease and benefit the management and disposal of all wastes and secondly improve the treatment and reuse of OFMSW within the cities. If waste is managed correctly, more spaces will be opened for biogas projects, creating incentive mechanisms and resolutions and enabling more participants on the subject [304].

Some researchers, such as *RTQBR03* and *RTQMX08,* argued that source segregation already makes a big difference if done in two groups (OFMSW and others), as it allows waste pickers to increase the level of recycling and at the same time avoids impurities in the organic fraction. Segregating the recyclables from tailings (and other contaminants) further improves the system, separating three fractions: organics, recyclables, and non-reusable garbage. It also brings other advantages such as minor impurities, significant feedstock quality for recycling, and socioeconomic benefits.

In Brazil, a program seeks to increase selective collection in the country, aiming to meet the management hierarchy according to the national solid waste policy (*RTQBR02*). In both countries, municipalities organize the sorted waste system, engage the householders, and set proper logistics to make it feasible and assure its effectiveness. Even though such techniques are still incipient throughout these countries, some municipalities are viably implemented, such as Curitiba in Brazil or Cherán in Mexico.

5.4.1.1.3 Feasibility of wet and/or dry biodigesters

There are diverse techniques for the treatment of OSW. Some of the interviewees, RTQBR02 & RTQMX06, pointed out the advantages AD technologies offer, especially for agricultural wastes in rural areas, and the convenience to expand the implementation of these technologies, mainly due to the latest developments on co-digestion and use of biomethane for vehicle fleets, which is already occurring in Brazil. In that sense, another question to the interviewees was on their perspectives if traditional wet and dry biodigesters are a feasible technology to treat this waste fraction. For what, almost 90% of them agreed and acknowledged their potential for the task.

Additionally, it was also pointed out by two of the researchers, *RTQBR03* and *RTQMX10,* that the implementation of these processes significantly depends on each substrate, conditions, and quantities; and both WAD and DAD technologies can attend the upward on waste hierarchy when it comes to treating the OFMSW specifically. In addition, the economic sustainability and management requirements should be assessed carefully for each case and situation. In some cases, as mentioned by *RTQBR01*, composting could be a less expensive and simpler technology option to manage. The waste composition is a significant driver when it comes to choosing one solution or the other.

5.4.1.1.4 AD technologies to treat OSW

This research emphasized determining the most appropriate technology to treat OSW residues in both countries. One more request to the specialists was to select one or two from Figure 4: General classification of AD types. Source: adapted from IBTech, 2020 [22] and explain why they credit that case.

The responses varied; however, the large majority (78%) argued that it depends on diverse factors according to the specific context (i.e., city, waste composition, among others.) where the facility is to be located, the scale of the project, characteristics of the substrate. All technologies have pros and cons; in Europe, for example, both technologies have been used for more than 15 years to treat various organic solid wastes (*RTQBR01*).

Additionally, even when they agreed that it depends on several factors, some interviewees argued in favor of both ways. Some (*RTQBR02*, *RTQMX09*) leaned towards wet digestion in a continuous mesophilic reactor due to the characteristics of the waste and the fact that wastewater can be used, and the digestion processes are relatively fast. On the other hand, others (*RTQBR04, RTQMX06, RTQMX07*) pointed their preference and advantages of DAD systems to keep the treatment as simple as possible; DAD - Bath - Mesophilic - One (or two) Stages. They argued that this technology is best for the solid fraction of the waste (e.g., residues from central markets or rural codigested solid residues) and does not have to be continuously fed, as in other cases. However, the financial viability must be considered since, until now, commercial production of these technologies in the region is very immature. Hence, the conditions for implementing biodigesters to treat the organic wastes are given, and their success mainly depends on their viability for the specific conditions of both countries.

5.4.1.2 DAD technical aspects

5.4.1.2.1 Reasons and challenges to implementing DAD systems

To find out why DAD systems have not been significantly implemented and promoted in both countries, it resulted in a list of options numbered in order of relevance. The results are presented in the following graph:

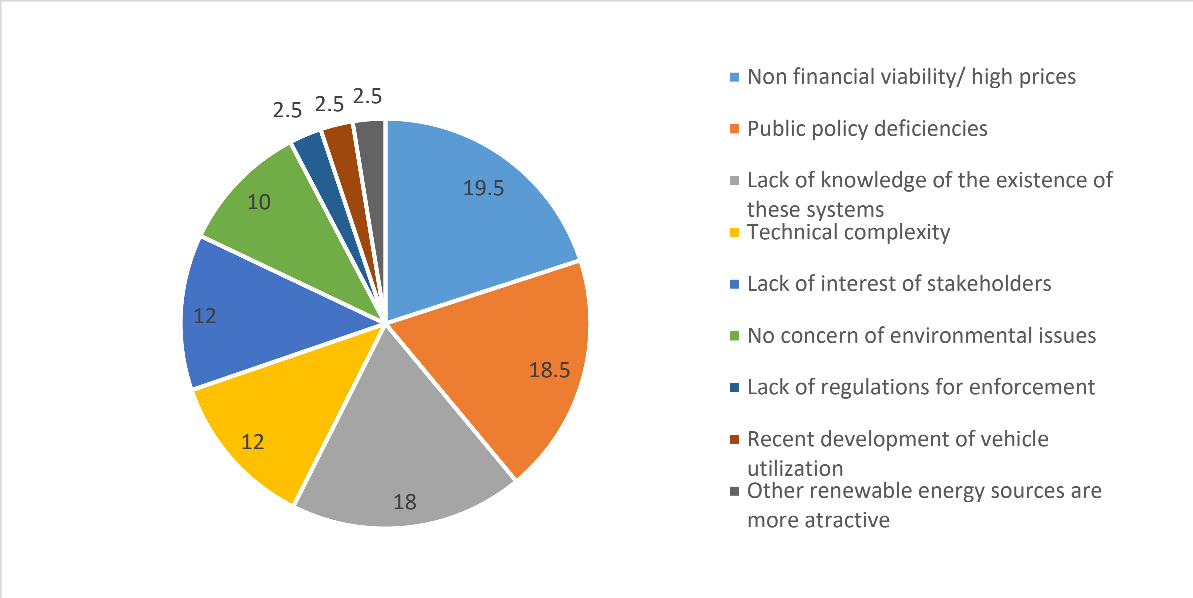


Figure 24: Reasons for low implementation of dry anaerobic digestion (DAD)

As it can be observed in Table 21. *Reasons* for the poor implementation of AD to treat OFMSW. Numbered in order of importance. (Number 1 = main reason); and/or "Na" if it does not apply, or no answer was obtained.

Table *22* and Figure 24, according to the interviewees, the main reasons for the poor implementation of DAD projects in Brazil and Mexico are: (1) high prices or the economic unfeasibility, since in most of the cases, the technology needs to be imported; (2) public policy deficiencies; (3) lack of knowledge of the existence of the systems. As the second stratus, the factors that still play an essential role in the inhibition of these technologies are (4) technical complexity of the technology; (5) lack of interest of the stakeholders such as investors or private companies due to the financial risks; and (6) no concern of environmental issues of decision-makers. Finally, other reasons that contribute to less extent are: (7) the lack of regulation for the enforcement of the implementation; (8) the recent development of technologies that can potentially use biogas, such as vehicles; (9) more attractiveness of other renewable energy sources.

5.4.1.2.2 Other Challenges to implementing DAD systems

As presented in **¡Error! No se encuentra el origen de la referencia.**, other challenges that were identified c onsidering the opinions of the interviewed experts and needed to be acknowledged are the following:

- Lack of technical knowledge and documentation (technology and biological processes) (*RTQBR02*);
- High operational costs (*RTQBR04)*;
- Poor substrate homogeneity and lack of mixture (*RTQBR05*);
- Lack of compliance with the law (*RTQMX09*);
- Make the use of biomethane compatible with the vehicle industry (*RTQBR03*), among others.

5.4.1.2.3 Less water utilization in DAD systems

One of the presumed main advantages of DAD over traditional WAD systems is less water utilization through its biodigestion processes. To find out more in this regard, one question to the specialist was on whether this represents a significant advantage for these technologies, for what the results show the following:

More than half of the participants (approx. 56%) agreed that it could be an advantage, mainly in the arid, semiarid regions and areas with few hydrological resources. However, other specialists (33%) stated that it depends on the specific circumstances, and WAD systems could utilize adequate wastewater to co-digest it with solid residues, which brings at the same time the benefit of wastewater treatment and non-potable water usage. Moreover, as pointed out by *RTQMX09*, where wastewater cannot be used, DAD projects can reduce potable water consumption for the digestion processes, for example, in specific decentralized agricultural projects. In addition, due to the needed more effective organic loading rates in WAD processes, the size of the reactors needs to be 30% larger than in DAD processes (*RTQMX07*), which could also represent an asset for the financial viability of DAD projects.

5.4.1.2.4 GHG reduction goals

As a renewable energy source, DAD technologies have a particular potential to reduce GHG emissions. Hence, another inquiry to the specialists was on their perspective if these technologies can significantly contribute to Brazil and Mexico to reach their GHG reduction goals, according to the NDCs goals. The responses were mainly affirmative (56%), mentioning that DAD technologies can mitigate GHG, firstly by the otherwise emitted methane CO_2 and other gases by landfills. Secondly, by saving the CO_2 emissions from fossil fuels replacement of energy production, regular transportation means by biomethane, mineral extractions, and humus production. A specialist, *RTQMX07*, mentioned that their actual contribution in Mexico is minimal, considering that just 1% to 3% of the country's energy needs can be obtained from organic residues, thus leaving a non-relevant contribution for GHG mitigation. The researcher proposes that other renewable sources such as hydrological, wind, and solar could be better implemented for this purpose. Therefore, specific measurements would be necessary to find out the GHG mitigation potential of large-scale biodigesters.

GHG´s emissions reductions with biogas in Brazil and Mexico

According to the World Biogas Association [310], at a glance, biogas can contribute to reducing overall GHG emissions by 18% to 20%, as a renewable energy source from food waste, industrial organic, and agricultural wastes, and sewage.

GHG´s reductions through biogas utilization can be achieved mainly in two ways: First, enhance the sinks of greenhouse gases as a renewable energy source that can replace fossil fuels. Furthermore, secondly, by source reduction; reduction of methane that would otherwise be released into the atmosphere with traditional organic waste treatments or no treatment at all [311]. Additional indirect GHG´s can be reduced by replacing synthetic fertilizers with the digestate or biofertilizers generated as a co-product of the AD processes. The reduction of pesticide uses, and water demand also is an indirect benefit of biogas systems.

Thus, GHG´s reduction with the biogas depends on the way biogas is utilized [310]:

1. GHG emissions reduction with electricity generation
2. GHG emissions reduction with heat supply
3. GHG emissions reduction with transportation services
4. GHG emissions reduction from urban organic wastes
5. GHG emissions reduction from agricultural wastes

As suggested by ABiogas in [29], Brazil can produce up to 82 billion m^3 of biogas annually. This biogas production can contribute to reaching the NDC´s national goals remarkably, attaining emission reduction goals. In 2020, the plants produced 1.83 billion m^3/year, equivalent to 2% of the total potential. Considering the current 37 plants in the implementation phase of reforms, the country will soon reach an annual biogas production of 2.2 billion m^3/year [28].

There is a current biogas production of 114 Mm^3/year in Mexico, estimated by Gutierrez (2018) [296]. The (Energy Secretariat) SENR, in its roadmap for biogas to 2030, in collaboration with the Gaseous Biofuels Cluster at the CEMIE-BIO, estimates a potential biogas production of up to 800 Mm^3/year [312]. This biogas production translates to potential mitigation of CO_{2eq} otherwise released. This emission reduction can also contribute to the country reaching the NDC´s national goals.

5.4.1.3 Economic

5.4.1.3.1 Future financial feasibility

As previously pointed out, one of the primary and most relevant reasons for the poor implementations of DAD digesters is their still inaccessible costs and non-financial viability, mainly since the technology must be imported most of the time. Another question to the specialists was whether these technologies could become more financially viable in the future and suggested what needs to be done to achieve this goal.

For the Mexican case, one of the interviewees, *RTQMX09*, mentioned that from previous experiences, the existing AD technologies are still not economically viable. The success of previous projects was just thanks to the political will of the governments in turn. However, most of the specialists agreed that economic viability could be achieved, stipulating enough demand and supply opportunities. For this to happen, they suggested as necessary the following points:

- To develop local technology products suitable for the country's realities (*RTQBR02*);
- To reduce system production and material costs (*RTQMX08*);
- Governmental incentives (*RTQMX09*) and benefits might be encouraged to start the projects and create better revenues from the energy production (in comparison with oil and natural gas) (*RTQMX08* and *RTQBR01*);
- Learn how to control the processes properly and produce energy at competitive costs (*RTQBR05*);
- Governments should also implement waste source segregation plans (*RTQMX07*);
- Include the private sector to profit their businesses from these processes (*RTQMX10*);

- Develop an understanding that the investment is recovered, and profits are gained in long-term periods (*RTQMX09*);
- To clear revenues from both biogas/biomethane to produce electricity of fuel and the quality digestate (organic fertilizer) (*RTQBR01*);
- Increase fees for the deposit of waste in landfills (*RTQMX09*).

As mentioned by *RTQBR05*, every technology has its scale economy curve. If they are applied, technologies become more competitive, as it already happened in wind energy and photovoltaics. For this, the best practices of regulation must be considered, and the incentives must be restricted to the results and not to specific technologies or solutions. It will be a real option if DAD achieves competitiveness with other treatment and energy production options that deliver the same results. Otherwise, other solutions will overcome it.

Alternatively, *RTQBR03* and *RTQMX07* mentioned, for both countries, that there is already economic viability for the implementation of these technologies, and the government must impulse and demand their implementation, which can also be seen to improve local health conditions.

5.4.1.3.2 Development of national technologies

A relevant factor for disseminating these technologies might be the development of national or local technologies adapted to the conditions and substrate characteristics where they are going to operate. We asked the interviewees if there is also the structural capacity and technical know-how for this to happen.

Half of the interviewed participants agreed that the structural capacity and technical knowledge (still missing some specific aspects for DAD technologies) are available to develop new local technologies in Brazil and Mexico, undoubtedly contributing to implementing more projects.

In the case of Brazil, the structural capacity and technical know-how to develop such technology are in the hands of companies (technicians and researchers) that operate the existing plants (national or foreign). Universities also count on practical and relevant research (*PPQBR11*). However, they also agreed that this technology development environment demands high investment costs and time (*RTQBR04*). Local suppliers can offer a competitive advantage in maintenance costs, operations, and others (*RTQBR05*).

In the case of Mexico, there is still a gap between research centers and the industrial sector, missing the bridge and link to generate knowledge and transform it into new technologies (*RTQMX10*). Moreover, RTQBR03 mentioned that proficient treatment of organic wastes via anaerobic digestion could be feasibly done with technology from any national origin.

5.4.1.4 Policy

5.4.1.4.1 Previous public policies and regulations

Brazil and Mexico have implemented public programs that foster the implementation of anaerobic digestion projects; however, especially in Mexico, in many cases, they have not continued and prevailed. The questionnaire also inquired the researchers on what are the reasons that caused this.

In Brazil, where AD has been thoroughly implemented, public policies that encourage biodigestion and co-products have revolutionized the bioenergy market for the past five years (*RTQBR02*). However, according to *RTQBR03*, there is still necessary to articulate and integrate the diverse influential sectors. Factors such as technology complexity or high investment costs must be considered in new regulations.

In the Mexican case, as pointed out by *RTQMX08,* a current factor that has hindered the implementation of new policies and programs for biodigestion systems is that AD technologies compete with policies that promote other systems for the generation of renewable energy, such as wind and solar. These are, to date, more attractive from an economic point of view. Furthermore, even when policies and incentives for implementing biodigestion systems exist, through the interview´s answers, it was also found out that one of the causes for their low implementation is that many of the projects that have been developed are not given continuity. In many cases, they were essential technologies that did not work proficiently in the long term, thus discouraging a significant number of stakeholders interested in the first place. This sporadic issue has caused the misconception that it is a process that does not work (*RTQMX06*). Another factor is that considering the vast amounts of available land, waste disposal in landfills or even dumpsites is still economically by far the most competitive solution (*RTQBR05*), despite the waste of resources and energy.

Furthermore, the treatment of OSW via AD is generally accepted as a solution; however, as mentioned by *RTQMX09,* the political rotation at the municipal, state, and federal levels is another factor that has inhibited the effective implementation of these types of programs. The specialist also mentioned that the time to foster and implement these technologies in many cases takes too long to be of genuine interest to certain politicians. One of the solutions would be to develop a federal or a state plan; however, up to date, there are still no directives or intentions towards it. The public policy situation in both countries is further analyzed in sections 5.4.2 and 5.4.3.

5.4.1.4.2 Flaws of the current legislation related to AD systems

In both countries, the legislation and regulations that encourage AD systems for OSW treatment (see section 5.3) are not attended in many cases. One more question inquired on the researchers´ and specialists' opinions on the reasons for this lack of attention.

Some researchers (*RTQBR05, RTQMX06 & RTQMX10*) concord that the existing legislation for the comprehensive management of urban solid waste should be better attended and is commonly not complied with since no one enforces it. Even when municipalities generally accept AD as a solution for OSW treatment, local authorities still do not have enough commitment to implement such technologies, such as reducing the high taxes on imported equipment and developing incentives for the private sector.

As mentioned through the interviews, additional amendments should be proposed to be included, such as:

- Implement the principles of circular economy as an adaptation to these existing laws (*RTQMX10*).
- Increase surveillance to prohibit irregular/inadequate disposal (dumpsites) (*RTQBR05*).
- Include the co-digestion processes in the legislation (*RTQMX10*).
- Raise consciousness for the adequate disposal of residues at a societal level (*RTQBR05*).

- Develop on implementing specific technologies or new developments (*RTQMX07*).
- Integrate sectors for technological innovations (*RTQBR03*).

In Mexico, as pointed out by *RTQMX09*, the responsibility to collect, dispose and treat waste is until now of municipal order. In that sense, it was suggested that the burden could be passed to the states, bringing some municipalities together and thus streamlining processes and contributing to the viability of the projects.

5.4.1.4.3 Current policies contribution

The policies, which are currently implemented, are in different degrees contributing to the dissemination of AD in both countries.

The biomethane regulations, the RenovaBio program, and others help distribute more projects based on AD technologies in Brazil. Landfills are no longer seen as the optimal option for treating the OFMSW, and decision-makers are paying more attention to AD technologies. This perception is especially considering the high demand for fuels for the transport services (garbage trucks and urban buses) mainly operated by City Halls or concessionaires (*RTQBR03*). Biomethane markets are already starting to attend to these fuel demands.

In Mexico, the implementation of hundreds of digesters was achieved through promotional programs funded by FIRCO-SAGARPA in the early 2000s, mainly for the treatment of agricultural wastes. The National Biogas Commission (CNBiogas) is currently pushing towards implementing more biodigesters, but still with minor results (RTQMX07). For OFMSW, however, as pointed out by RTQMX06 current regulation still focuses on sanitary landfills as the optimal option, and bioenergy is not considered relevant (RTQMX10).

5.4.1.5 Recommendations

Finally, it was also asked directly to the interviewees for other recommendations on how to foster AD technologies for the treatment of OFMSW, hereafter, their responses:

- Demand on diesel oil by public transport services (such as garbage trucks and urban buses), operated mainly by City Halls could be supplied by the biomethane produced with the urban and rural OSW (*RTQBR03*);
- Expand AD projects to the rural market (*RTQBR03*);
- Develop the policies to avoid landfilling and foster the harnessing of material or energy waste content (*RTQBR05*);
- Demonstrate the advantages of biodigestion for potential producers - especially of medium and large scale, to take this information with technical quality. These technology promotions could be through technical seminars such as ABiogas is carrying out in Brazil (*RTQBR02*);
- Looking for adequate investments and attractive long-term contracts at the same time remain as one of the main challenges (*RTQBR02*);

- Share successful cases with decision-makers; develop pilot plants through research centers to demonstrate that these technologies can succeed (*RTQMX09*). This successful pilot plants would raise interest in the private sector which would be a key factor; hence, not depending totally on the government. A private project with international support could be the example to follow, which could help to open the biogas market;
- Encourage the participation of the private sector and create incentives for private companies (*RTQMX10*);
- To generate a report of the AD systems at a national and international level, which contains general information such as performance, materials, costs, equipment (*RTQMX08*);
- Include more participation of society and understand the utility regulatory role that it represents (*RTQBR05*);
- The promotion of events that allow the exchange of practical, technical, and economic knowledge, bringing together specialists, public authorities, market developers, and potential investors (*PPQBR11*);
- To promote practical projects where companies are associated with universities that seek to solve problems (*RTQMX06*);
- More awareness could be raised to disseminate the technology and demonstrate the viability of AD, with some programs or political strategy (*PPQBR16*);
- To have a specific public policy for MSW, with biogas generation, giving support to municipalities, or consortia of municipalities, carried out by the federation and states (*PPQBR12*);
- Development of AD by dry route for small volumes and local uses, avoiding as much as possible the transportation of the substrates (*RTQBR04*);
- The risk of failure to manage an AD technology needs to be carefully considered since there have been cases when they do not reach viability (*RTQBR01*);
- Source segregation of residues is very relevant for the success of AD digestion technologies within urban spaces (*RTQBR02*);
- Create transversality within all the existing politics to follow the same pattern, pursuing the same results (*RTQBR05*);
- The development of biodigesters in small towns for self-consumption and small scale must also be under the loop (*PPQMX19*);
- For Mexico, anaerobic digestion is the best solution for treating OFMSW and many other agricultural residues; without neglecting the opportunity of other thermochemical technologies and composting to treat specific organic residues. There are millions of tonnes of organic waste in the country; it is just a matter of doing the proper management (*PPQMX23*);
- The management of AD technologies is essential for the success and economic profitability of the projects (*RTQBR01*);
- Promote the implementation of anaerobic reactors to treat the residue sludge derived from wastewater treatment plants (*RTQMX10*).

5.4.2 Public policy specialists in Brazil

The arguments now presented resulted from the integration of diverse opinions from public policies specialists. The information integrated resulted from conferences, online forums related to public policies and biogas; together with the interviews carried out to public policy specialists and stakeholders from the following Institutions (in order of intervention): Environmental Company of the State of São Paulo (CETESB); United Nations Organizations for Industrial Development (UNIDO); Parana State Secretariat for the Environment and Water Resources; International Center on Renewable Energy/Biogas (CIBiogas); Network of Biodigesters for Latin America and the Caribbean (RedBioLAC); Institute of Energy and Environment/ The University of São Paulo (IEE/USP); and the Brazilian Association of Energy Recovery of Waste (ABREN – WtERT). Complementary notes from secondary sources, such as reports and scientific articles, were also considered. Hence, the following information represents the integration of this information for each topic.

5.4.2.1 Current policies

5.4.2.1.1 Low carbon energy systems and successes achieved with the current expansion of biogas in Brazil

The Brazilian government seeks to reduce carbon emissions and has created diverse strategies. Environmental services have considered, for instance, the production and use of biomethane as a valuable service. For this purpose, there is already support for a chain of products suppliers and services, leading to an increase in the institutional competitiveness and technological environment (*RTQBR04*). Hence, as stated by *PPQBR13*, the implementation of biogas projects is aligned with the trend to implement low carbon energy systems towards compliance with the NDC reduction targets derived from the Paris Agreement.

Brazil has passed the phase of technological proof and overcoming the technical barrier (*PPQBR14*). Biogas systems for the generation of electricity and biomethane have been lately expanding in Brazil, mainly in urban waste landfills, sewage systems, and the livestock sector. As pointed out by *PPQBR14*, most of the stakeholders are looking for them to be economically viable and see them as a profitable business. The specialist also mentioned that there is currently a search for their economic viability and efficiency of new technologies to valorize all products resulting from the processes. Thus, seeking revenues not only from biogas but also from digestate, the mitigation of CO_2 gaining with the emission reduction; thus, improving the financial viability of the projects.

According to data from 2019 from CIBiogas, mentioned in the interview *PPQBR12*, biogas has its most significant production in the primary sanitation sector (garbage and sewage), where it represents 76% of biogas production in Brazil. The primary sanitation sector is the main biogas generator, and electricity is the country's leading destination. According to data from the Panorama of Biogas in Brazil in 2020 (CIBiogas), from all produced biogas, 73% is destined for the generation of electric energy, secondly for the generation of biomethane (19%); and thirdly for thermal energy, with 8% [27]. Biogas has indirect stimulus in its expansion through public policies and regulations such as RenovaBio or the low-carbon agriculture plan from the Ministry of Agriculture.

Nevertheless, currently, there are no consistent policy advances; and there are no direct governmental incentives for biogas projects (*PPQBR15)*. There is still a lack of a more punctual policy force linked to reducing emissions via the treatment of solid urban wastes and sewage (*PPQBR14*). Biogas projects are not addressed in a specific state agenda, and the successful cases seen are more a result of a market movement rather than encouraged by the government (*PPQBR14*). Thus, biogas projects' late growth and development are mainly due to private interests via an open market system.

Policy advances are more at the state level. In the state of São Paulo, the local government´s current policies include leading low-carbon energy systems, and biogas participation is moderately increasing its involvement in the energy matrix (*PPQBR11*). Other states, such as Goiás, Paraná, Rio de Janeiro, Rio Grande do Sul, and Santa Catarina, have biogas and biomethane policies, as described in section 5.3.3.

5.4.2.1.2 Current regulations: RenovaBio, PNRS, PNE, & PDE

The RenovaBio program was established in 2019 by the ANP initiative. It is a program policy that encourages the development of bioenergy projects through carbon credits; however, with numerous projects being supported for ethanol and biodiesel, biogas is still the least biofuel considered. This program currently helps projects that are viable for biomethane, which are not all, and still have resources to invest in certification, limiting the potential of biogas projects (*PPQBR14*). Hence, a question to the public policy specialist was on whether they acknowledge feasible opportunities to improve this law to incentivize more the implementation of biogas projects; hereafter, some of the suggested improvements to this regulation:

- It could incorporate and encourage the use of the biogas already produced in many landfills by establishing progressive goals for biomethane use in vehicles and gas distributors (*PPQBR11*);
- It could further encourage the implementation of biogas projects by improving conditions for the generation and commercialization of CBIOs, with a focus on small and medium biogas producers, who are currently unable to afford the Program´s costs (*PPQBR12*);
- It could include a new mandate to encourage the generation of biogas credits, either by direct or indirect subsidies (*PPQBR12*);
- Officials could also create robust programs, projects, activities, and actions to implement this law (PPQBR13).

Furthermore, as pointed out in one of the interviews, a limitation of the program today is that it is restricted to biomethane marketed for use in transportation (*RTQBR04*). If a plant produces biomethane for its fleet, it does not generate CBIOs, unless it manages a sales process; this fact makes the CBIOs more expensive, the operation more complex, and transaction costs increase (*RTQBR04*). Thus, the law could also be adapted to consider the biogas consumed internally, generating CBIOs for this concept (*RTQBR03*).

In addition, another relevant point is that the cost for monitoring is relatively high, which restricts the project's eligibility for the increased scale of production and commercialization of biomethane (*RTQBR04*).

Furthermore, due to the current pandemic situation, The Ministry of Mines and Energy has reduced RenovaBio targets, which has resulted in a considerable reduction of biofuels production (mainly ethanol). Up to date, the situation is returning to normal; RenovaBio's goals that have been changed so far have not been readapted. Nevertheless, according to *PPQBR15*, biodiesel and bioethanol projects have increased by a certain percentage.

As for the PNRS, it is a policy that already defines the energy recovery of waste. Governmental officials are currently revising and improving this regulation, including guidelines to better the energy recovery from Urban Solid Wastes. These guidelines aim to identify technical, economic, and market challenges to define strategies to overcome them (*PPQBR11*). In addition, one of the interviewees, *RTQBR04*, stated that this revision and improvements should be evident in the medium term to design routes for the recovery of organic waste, such as electricity generation, compensation in public buildings, and the production of biomethane for urban bus fleets. Other improvements that could occur according to the specialists are:

- Define the mechanisms to enable the agencies to monitor and enforce the compliance of the law and respect the waste treatment hierarchy (*PPQBR14*);
- It could encourage the consortia between municipalities, which can be developed to manage waste between several cities (*PPQBR15*);
- Financial efficiency shall also be considered for the public sector (*RTQBR04*).

As presented in [313] for the PNE, biogas is included many times in the Plan; however, most of the time, it is mentioned in a very general way, lacking reliable data; as if it was a technology that is just starting. Information asymmetry, as if they do not have enough information of that energy source. Natural gas is still considered in this law as an energy source for future developments and often does not leave room to be substituted by biogas technologies. The Plan can consider biogas technologies to a more significant extent. It shall also include actual data and goals, considering that Brazil has already gained knowledge on the topic with more than 500 biodigestion plants throughout the country and many successful cases. More precise plans could be instituted according to the vast information already developed by institutions such as ABiogas, CIBiogas, EPE, and others, and negotiate with the Ministry of Energy and the EPE significant participation of biogas in the energy matrix [313].

Additionally, the Ministry of Mines and Energy presented in the Forum "Panorama of Biogas in Brazil" [304] a series of recommendations to the PNE 2050, applicable to biogas and biomethane, as shown in the following table:

Table 23: Challenges and recommendations for the PNE 2050 improvement. Source: Ministry of Mines and Energy presented in the Forum "Panorama of Biogas in Brazil" [304].

Challenges	*PNE 2050 recommendations applicable to biogas and biomethane*
Institutional conditions	Adapt institutions, regulations, and market arrangements to enhance biogas and biomethane in the energy transition.
	To articulate energy policies with Science, Technology, and Innovation policies.
Decarbonization	To have new products to promote energy efficiency and innovation actions.
	Articulate with other sectors and decision-makers the consistency of decarbonization policies and measures.

Fuels sector	Develop a roadmap for the use of biomethane.
	Develop biomethane quality monitoring systems.
	Develop public policies to enhance small-scale projects.
	Increase the attractiveness of biomethane in transportation.

Another relevant regulation for implementing anaerobic digestion technologies is the PDE (*Plano Decenal de Energia*), which already mentions the possible contributions that biogas can bring to the energy matrix in Brazil. The specialist inquired on their perspectives on if this regulation should include a more significant portion of biogas in the energy matrix by 2029. Most of the respondents agreed that the PDE should improve the scenarios for biogas, considering that it has great potential, where currently only 2% of that potential is exploited (*PPQBR12* and *RTQBR04)*. As mentioned by CIBiogas (2021) [28], Brazil today produces around 1.83 billion m^3 of biogas per year. According to ABiogas, Brazil can deliver up to 82.5 billion m^3/year with adequate management, considering the sugar-energy, sanitation, animal protein, and agricultural production sectors [28]. The growth has been 30% per year for the past five years (*RTQBR04)*.

Thus, the regulation could present higher scenarios, including a more significant portion of biogas in the country's energy matrix (*PPQBR15)*. For this to happen, the Plan should also present more specific information about the potential of the process to gives politicians more security to enter this data; and together with this, consider the additional attributes of biogas, so it is not only energy but a reduction of emissions, and fertilizers production (*PPQBR14)*. These changes could also result in the provision of state funds and subsidies to support biogas projects.

5.4.2.1.3 Other political instruments, new laws, or regulations to expand biogas

As previously stated in section 5.4.1.2.2, some of the present challenges to implementing biogas projects in the national energy matrix are the development and adaptation of the technology, investment and operational costs, and the lack of interest from stakeholders, among others. Hence, political instruments to overcome these challenges will be of great value, thus enhancing all services related to biogas production from organic waste. Here it resulted in the following political instruments suggested by the interviewees:

1) A biogas federal regulatory framework: providing a guide for biogas policies, competencies, incentives, and resources for their implementation (*PPQBR12*);
2) Parting from this national policy, state plans could be derived, which can adapt to the particularities of each state. These new policies could be implemented through certain state agencies to provide more security for investors and more harmonious regulations between the state and the federation (PPQBR14).
3) Specific credit lines for new biogas projects, subsidies, and working capital from the diverse ministries (PPQBR12);
4) Auctions for specific electricity and biomethane from biogas (PPQBR12). With this, there is no need for subsidies because it encourages the development through the market (PPQBR15);
5) Specific policies for fleet methanization, mainly for large urban centers with the use of locally generated biogas (PPQBR12);

6) Specific policies for the treatment of MSW and sewage sludge, with the generation of biogas in the treatment of the organic fraction; and the use of the biogas generated (thermal, electric, and transport) (PPQBR12);
7) Developing an environment for remunerating the generation of renewable energy services (RTQBR04);
8) Recognize the production and use of biogas as an environmental service (RTQBR04) lawfully;
9) Having less bureaucracy for the market strategies for biogas projects (RTQBR04);
10) Some propose that it is unnecessary to have a specific policy but a special commission of biogas at the federal level that includes several ministries in a more transversal way (*PPQBR14*).

5.4.2.2 Social contributions

WtE technologies based on biogas generation can be an agent for social development, especially the informal sector and less advantageous people such as garbage pickers. One more question asked for the participants' perspectives on how these technologies can improve social conditions and the importance of public participation.

Most respondents stated that implementing these technologies would contribute to social development by creating formal jobs, providing healthier work conditions, and reducing electricity and transportation costs for society. Rural communities might also benefit from the use of agricultural residues aimed at small farmers [308]. Also, being a low-carbon energy system, these technologies help to reduce the overall carbon footprint and other emissions, which is directly translated into public health.

It was also pointed out in *RTQBR14* interviews that society's participation in decision-making is essential mainly to create demands for implementing these projects. Society needs to be more aware of waste generation's social and environmental impact (*RTQBR14*). *PPQBR1* mentioned that it is also essential to create means to improve the public's perception, making information accessible to facilitate the interest of individuals for the treatment of urban organic waste through anaerobic digestion, and understand all the benefits obtained with this proper waste treatment method.

5.4.2.3 Environment and sustainable use of natural resources

Arable land occupation, forest degradation, biodiversity impacts are some of the possible environmental impacts that biofuel developments (mainly first generation) can cause. The expansion of bioenergy projects many times disregarded these environmental impacts. The next question asked the specialist what could be done to include these precepts in the current regulations and mitigate these impacts.

Even when some of the respondents had not considered this fact and did not give a straight answer, some (*PPQBR11, PPQBR14, PPQBR1*)*5* responded towards incorporating in the current legislation measures and restrictions to use new areas for bioenergy generation and restrict to the utilization of the available lands. Biogas and other biofuels should be produced, avoiding forest exploitation or other new lands (*PPQBR11*). Biogas projects should be kept as an accessory for rural producers, agro-industries, and the food industry to treat organic wastes. Always with the precept that this energy generation system shall contribute to saving resources and mitigate environmental impacts. Biogas should be produced primarily from waste and residues, thus giving credits to these cases (*PPQBR14*).

In this sense, Brazil is on the path of obtaining biogas from urban and rural organic wastes; and the current deforestation issues are not due to biofuels but because of the illegal timber trade (*PPQBR15*). Nevertheless, in the few cases that biogas is obtained directly from 1st generation plantations, it shall be essential to place strict regulations and limitations so that it is not expanded without measure (*PPQBR14*). According to one of the specialists, *PPQBR14*, it could be allowed just when certain conditions are applied, for example, to rotate the plantations and protect soils.

5.4.2.4 Energy market

5.4.2.4.1 Opportunities and barriers of biogas markets in Brazil

The new gas market in Brazil has implemented recent regulatory changes aiming to end the state-owned oil company Petrobras monopoly, open the market, and increase foreign and national investments. This changes certainly have a favorable influence on the biogas sector. Thus, the study looked for these new reform's opportunities, barriers, or challenges with one more question. From the responses, the following was identified:

Opportunities:

- Expansion of the biomethane consumer market (*PPQBR12*);
- Expansion and availability of equipment that uses natural gas (*PPQBR12*);
- Expansion of infrastructure and services (transportation, processing, and distribution) for the biogas sector (*PPQBR12*);
- Expansion of the gas pipeline network to points distant from existing gas pipelines (*PPQBR12*);
- Further development of technologies and processes (*PPQBR14*).

Challenges and barriers:

- Lack of a regulatory framework for biogas (*PPQBR12*);
- Lack of gas pipelines in regions with great potential for biogas production (*PPQBR12*);
- Lack of compulsory biogas mixtures (*PPQBR12*);
- Lack of public policies to encourage fleet methanization (*PPQBR12*);
- Lack of incentives for the development of national technologies (*RTQBR04*);
- Hindering bureaucracy for the development of biogas projects (*PPQBR13, RTQBR04*);
- Low competitiveness of costs and price of biogas energy with other energy sources (*PPQBR11*);
- Natural gas is often very competitive since it is given even for free in some regions that have oil platforms. These are due to their regulated flare limits (*PPQBR14*);
- Information asymmetry (*RTQBR04*).

Additionally, as pointed out in one of the interviews (*PPQBR14*), it is important that biomethane is differentiated from natural gas and recognized for its properties of being a gas with other advantages such as reducing emissions and low environmental impact, among others.

Thus, an appealing path can be the injection of biomethane into the gas network, making a mandatory percentage mixture with natural gas (*PPQBR15*). However, it is not a simple political path. For example, and brought by *PPQBR15*, São Paulo officials have been trying to include this mixture with biomethane for several years, but they have not succeeded until now.

5.4.2.4.2 Biomethane vs. diesel, gasoline, and ethanol for transportation

The Biomethane market as a fuel for heavy load trucks in Brazil is currently expanding. To further understand and affirm its viability, this research addressed the specialist on their opinion on whether biomethane should be more incentivized than gasoline, diesel, and ethanol as urban transportation and heavy load trucks fuel.

All the respondents answered affirmatively. Biomethane should be fostered for its production and consumption as urban transportation fuel, considering its low carbon footprint and mitigation to environmental impacts caused by gasoline and diesel. It is an efficient option to replace diesel in cargo transportation, buses, and heavy load trucks. As pointed out in the Biogas and Biomethane Forum in South Brazil [304], biomethane has the opportunity to supply up to 53% of the 7.2 billion liters of diesel used by the agricultural sector. Biomethane can replace it in fleets or vehicles that work with this energy source since it has similar chemical properties to natural gas. There just would have to be a more robust system for its distribution (*PPQBR15*).

Additionally, the production of biomethane in diverse regions and decentralization of biofuel generation becomes important considering that oil is produced on the coast and there is a large consumption of diesel in the interior of the country due to agriculture. This becomes an advantageous characteristic for biomethane.

Additionally, it was argued that it is not a single measure to address the issue, considering other biofuels such as ethanol or hydrogen. In many cases, these do not compete but are rather complementary (*PPQBR14*). Each has its specific advantages and characteristics that can adapt to different situations such as market development or technology, be implemented in certain regions (*PPQBR14*). Hence, it should be applied where it is suitable and viable.

As mentioned by PPQBR16, Brazil already encourages ethanol production due to its fraction obligatorily added to gasoline. Thus, there is an opportunity for a policy to use biogas as a fuel to replace natural gas (CNG) and or diesel in vehicles, resulting in a direct incentive for investors to have a guaranteed return. Likewise, there is an obligation to add a particular portion of biodiesel to diesel.

5.4.3 Public policy specialists in Mexico

The arguments here presented resulted from the interviews with stakeholders and public policy experts from the following Institutions (in order of intervention): Mexican Association of Biomass and Biogas (AMBB); Institute of the Americas; Experts in Solid Waste Management (ECOTEC); former member of the Secretary of Energy; ELNSYST, S.A. DE C.V. (IBTech®); Faculty of Engineering - Autonomous University of the State of Mexico / Mexican bioenergy network, A.C. (REMBIO); National School of Biological Sciences

(ENCB) of the Polytechnic National Institute (IPN); and the National Chamber of the Energy Industry (PROCNIE A.C.). These, together with complementary notes from secondary sources such as conferences, forums, and scientific articles. Hence, the following information represents the integration of this information for each topic.

5.4.3.1 Antecedents and current policies

5.4.3.1.1 Previous initiatives and attempts to install biogas projects

Initiatives and attempts since 2005 have implemented several biodigesters and covered lagoons throughout the country via financing systems regulated by the Institutions Firco/SAGARPA. However, these financing programs have not achieved the expected results on more and efficient biodigesters implementation. Currently, there are no more than 500 biodigesters in function out of the almost 1700 that were installed. Hence, attempting to find out the reasons for this situation, the specialists were questioned on their perspective in this regard.

According to the interviewees, some of the factors that have hindered or not helped the further effective development of these initiatives are:

- They were focused on small plants, between 200 to 500 KW, designed for self-consumption; thus, the farmers could not submit the energy to the matrix, which could have generated additional income (*PPQMX19*);
- Limitation of the cover lagoon technologies to handle only very diluted substrates such as manures (*PPQMX21*);
- There were failures by SAGARPA and FIRCO because they gave away financing of more than 1 million pesos for the motor generators. Many were built and are poorly managed. From 3 months to 1 year, the motor generators were broken down by H_2S, and capital resources were not enough to maintain the systems; the cost of the technologies demanded considerable subsidies to be maintained afloat (*PPQMX20*);
- These financial credits were often not paid, and farmers had to seek financing with CFE (Federal Electricity Commission). With this, there was no possibility of recovering what they had invested in micro turbines or engines because the financial Institutions stopped paying them, and thus they requested the support of CFE; therefore, a market failure was generated (*PPQMX23*);
- The farmers and service providers stopped paying back the subsidies since there was no significant penalty for their non-compliance. Thus, little by little, stakeholders stopped investing when they perceived that they did not recover their capital (*PPQMX23*);
- Knowledge of biodigestion was low, and there was little connection to the private and public sector (*PPQMX19*);
- It was not financially appealing, e.g., the farmers had no interest in paying for the digestate (nutrients); and technologies demanded considerable maintenance costs (*PPQMX19*);
- Lack of normative regulations and specific policies to allow further development of this type of project (*PPQMX18*);

Regardless of this situation, as pointed out by *PPQMX20,* the abandoned and out-of-service biodigesters can be recovered with the right policies. A recuperation program could be set considering the will of farmers.

5.4.3.1.2 Clean Thermal Energy Certificates (CETEL)

Currently, there are no relevant governmental incentives or subsidies for bioenergy projects in Mexico. Gutierrez, 2018 [296] suggested that with the creation of the Clean Thermal Energy Certificates (CETEL) - as it already exists with Clean Energy Certificates (CEL) - greater participation of biogas in the national energy matrix could be encouraged. One more question asked the interviewees how relevant this could be; for what it resulted in a diverse range of opinions and perspectives, further presented:

70% of the respondents agreed that creating the CETEL´s could work and be an effective initiative to open and stimulate the bioenergy market as a solid contributor to suffice the thermal energy demands. The creation of CETEL´s would allow that thermal energy technologies compete and not against different types of energies, as it currently happens with the CEL. This current situation has caused uneven competition considering the lower costs in generating electricity from wind, solar and hydro sources. For example, as mentioned by one of the specialists, *PPQMX23*, in the last two years ago, 69 million new clean energy certificates for hydroelectric plants are being allowed to enter the market. This inclusion has arguably caused a market distortion because as so many CEL´s for hydroelectric energy enter the market, other producers or generators are no longer interested.

Thus, it is very relevant not to mix the types of energies within these certificates. Natural thermal energy (natural gas and biogas) obeys other industry reasons than electrical energy supply. Thus, it is essential to distinguish between electrical and thermal energy, considering that thermal energy is more oriented to demand and electric to supply (*PPQMX23*).

Alternatively, one of the specialists, *PPQMX19*, mentioned that the best thing would be to leave the existing CEL and modify the auction processes to focus on the type of technology. Aside from this, another specialist, *PPQMX20*, does not think such an initiative could be successful since, for the implementation of these technologies, energy production should not be the primary driver, but rather the treatment of waste and the recovery of nutrients. They mention that the primary function of a biodigester is sanitation rather than energy production.

Thus, considering the diversity of answers, it is recommended to conduct a market analysis first for such a policy to prosper. In case CETEL´s result in a viable policy, it was also pointed out that there must be an official control body to regulate and monitor these certificates since their consumption is internal to the energy industry (*PPQMX21*).

5.4.3.1.3 Current laws and regulations

Promotion programs such as PRONASE and PROINBIOS

Renewable promotion programs such as PRONASE, and PROINBIOS (among others), have promoted the participation of renewables. However, bioenergy and biogas technologies have lagged in the country's last places of clean energy [288]; thus, public policy specialists were asked how to increase biogas participation in these or other renewable energy programs.

Historically, in Mexico, biogas has been an undesirable by-product of the original approach to garbage collection. According to *PPQMX23,* it is not competitive for its use in the production of electrical energy. Thus, biogas projects must open their way because the government does not support them as an energy source. The last energy reform in March 2021 that Mexico had mainly prioritized the parastatal organizations Federal Electric Commission and Mexican Petroleum Company (CFE and Pemex) over any private interests, let alone electricity from renewable sources. Anaerobic digesters are, to date, not considered in the energy strategies. Furthermore, according to *PPQMX19*, the development of a new specific regulation focused on biogas already began in past years but did not advance any further.

On the other hand, from a market perspective, in recent years, as mentioned by an interviewee, *PPQMX23*, biogas is being reassessed in a market that did not exist before, and he believes that it is the market for vehicular fuel. Also, as the specialist mentions, several companies are turning to see it as cheap energy; since it does not necessarily need to be transported by a gas pipeline and compressed in tanks. This interest did not happen before because gasoline, diesel, and natural gas were inelastic resources; however, currently, it is no longer so, but they are relatively entirely replaceable or even undesirable, even with their considerable high calorific values. These fuels also have other environmental impacts that neither natural gas nor biogas has. Accordingly, it is just a matter that authorities see and grasp this opportunity and create incentives for its dissemination. In summary, the exchange value biogas has, is the replacement mainly of natural gas and diesel.

Another efficient practice would be to stimulate the development of capacity and knowledge. For example, the development of CEMIE-Bio with its five clusters was a great initiative to promote research on the subject and bring together the academic sector to generate knowledge and eventually translate it into commercial applications. To the extent that this technology can compete with other energy and nutrient sources, projects could be massively developed from these resources (*PPQMX18*).

One of the specialists, PPQMX20, also highlighted that for biodigesters to prosper, the precept that everything must go to generate energy must be removed; to avoid this type of confrontation with the state. The focus must go to sanitation without getting too much into power generation, considering that biodigesters are more a matter of safe waste treatment. Thus, there is much to improve in waste management systems; there are no garbage segregation programs where municipalities separate waste, characterization studies are required, among many other needs for biodigesters to prevail (*PPQMX22*).

"Law for the Promotion and Development of Bioenergetics", "Energy Transition Law", "General Law on Climate Change" and "General Law for the Prevention and Integral Management of Solid Waste"

These laws are the ones currently related to bioenergy and waste to energy. Then a question asked the respondents whether there could be any reforms or additions to these laws to incentivize biogas projects.

One of the respondents (*PPQMX23)* suggested that these laws lay the entry barriers and must be a significant influence. The Law for the Promotion and Development of Bioenergetics presents a catalog of command-and-control restrictions that poorly suggest anything to favor the propagation of Bioenergetics but rather restrict them in their competition with food crops. These restrictions obey a regulatory logic that proposes to promote requirements for command and control and of great poverty in environmental matters (*PPQMX23*).

There are other issues in the Electric Industry Law, which with the new reforms of March, fossil energy is favored (*PPQMX23*). The specialist believes that this leads to consider that self-supply, distributed generation, or isolated supply is the way for biogas projects to thrive. Biogas can contribute in a virtuous circle if it is thought of as the source of natural gas for distributed generation and isolated supply. For this, the interviewee feels that it is not necessary to modify the law, but rather that the logic of the markets be oriented so that everyone can solve their problems with biogas. It is also required to take advantage of biogas coming from sanitary landfills to supply this energy.

PPQMX18 argued that since the technology is not mature, these laws should include stipulations to invest in research and development from the public sector and venture capital funds. Hence, once technological maturity is reached, it will be able to compete with other energy sources. These competencies should give all the responsibility to a single Institution and not distribute it, i.e., only to CRE (Energy Regulatory Commission) and not SENER (Energy Secretariat) (*PPQMX19*).

On the other hand, as mentioned by one of the interviewees, *PPQMX19*, the "Climate change law" does not directly support the development of biogas technologies, which should also be amended. Also, this law must consider the great value of the digestate to enrich soils since this indirectly mitigates climate change (*PPQMX20*). Additionally, derived from this law, each municipality must develop a Municipal Climate Action Plan (PACMUN). However, this plan is usually lagging or not contemplated in municipal development plans, and further deters the opportunities for climate change mitigation programs within municipalities (*PPQMX22*).

"General Law for the Prevention and Integral Management of Solid Waste"

Regarding waste management, just recently, on January 18th, 2021, a reform to the "General Law for the Prevention and Integral Management of Solid Waste" was published, which centrally stipulates that solid organic waste can be used for electrical energy recovery, which was an essential modification. Nevertheless, as one of the interviewees mentioned, *PPQMX23*, there is still a lack of methodology or strategy to make waste to energy a reality in the country.

Furthermore, this modification orders that the energy produced from the waste must be used for conversion to electrical energy, which according to *PPQMX23,* is incorrect because the electrical energy produced with biogas is not competitive and rather very expensive. A case that could be highlighted is the one in Salinas Victoria, Nuevo León, which has electricity for public lighting and the Monterrey metro with the OFMSW. However, it is a large amount of garbage with five municipalities.

Furthermore, strengthening regulation and enforcing waste treatment would help provide more significant incentives to reduce the costs, and thus, these technologies can eventually compete (*PPQMX18*). According to *PPQMX18*, an official Mexican normative for the management of this type of waste could help the enforcement and at the same time encourage companies to invest in learning more about how these technologies can reduce their compliance costs.

"Transition Strategy to Promote the Use of Cleaner Technologies and Fuels, 2019", and the "Intersecretary Strategy for Bioenergetics, 2009"

National Strategies such as the "Transition Strategy to Promote the Use of Cleaner Technologies and Fuels, 2019" or the "Intersecretary Strategy for Bioenergetics, 2009" also include biogas as an energy source. However, as all the respondents agreed, they do not consider bioenergy technologies sufficiently to contribute to their effective implementation and meet clean energy and energy efficiency goals. The recent Transition Strategy stipulates that the energy transition should be sovereign. It seeks to re-centralize energy sources, and biogas is not a topic of interest but rather the combined cycle of natural gas, coal, and fuel oil. With this, as suggested by *PPQMX19*, it can even be presumed that maintaining bioenergy was a victory. It was also argued that it is essential to have a diversified portfolio and not concentrate on various technologies to help achieve the GHG reduction goals.

Additionally, as suggested by various interviewees (*PPQMX18, PPQMX20, PPQMX21*), one of the main problems of these laws is their degree of non-compliance, and it is recommended to apply stricter means to determinately enforce their compliance. Accordingly, these laws lack the punitive element, such as going up fines for non-compliance.

Other laws

Additionally, it was also inquired to the specialists whether any other new policies or reforms could be carried out to promote the treatment of the OSW and other organic residues through anaerobic digestion. The purpose was to find a possible more effective and favorable policy (new law, strategy, or program). Their responses included the following recommendations:

- Make a report of the current regulations, which focus on bioenergy (*PPQMX19*).
- Invest in research, technological development, and innovation to make processes more competitive. For this purpose, it is worth channeling resources to energy sector subsidies focused on research and development and their projects, v.gr. CEMIE-Bio (*PPQMX18*).
- A new national normative (NOM) for the treatment of digestate, including specifications for the diverse types of wastes and conditions of the various organic wastes (*PPQMX20*).
- Release governmental funds to develop demonstration projects that successfully portray the state-of-the-art technologies (*PPQMX21*). These pilot projects would foster the involvement of the private sector and play a key role in allowing the market to open. New programs can be generated where the organic fraction is valuable and granted to private companies (*PPQMX22*).
- Develop and be more open to economic instruments, which will motivate the implementation of biodigesters. Experience has shown that attempts with command-and-control mechanisms have

> not proficiently worked in the country, mainly due to their financial dependence and low competitiveness (*PPQMX23*).

One of the specialists (*PPQMX22*) also suggested that these policies must be implemented at municipal levels to comply more directly. On many occasions, federal waste management and bioenergy regulations are not applied, and there are no penalties for non-compliance. *PPQMX23* suggests that municipalities should turn to qualified energy suppliers and stop relying on CFE. The specialist also suggests that municipalities require an alliance with state congresses to grant multi-year contracts; for what municipal cost-benefit analyses are required. The specialist believes that energy use should aim to reduce emissions, which applies directly to municipal legislation, and one should attend the federal law only concerning the electricity market.

At the Federal level, there is currently a new law under development about the circular economy (*PPQMX22*). In this, tools are generated to develop programs at the municipal level to see waste as reusable materials and not as garbage. However, as the interviewee mentions, it will be challenging to implement this new law if there are no resources for environmental programs.

Additionally, there is already the initiative in the Congress of Deputies under evaluation to create a specific law for Biofuels [314]. Very importantly, this initiative also pretends among various goals, the following:

- The harmonization of the national policies related to biofuels, described in section 5.3, including the new reform of the Electric Industry;
- The updating of programs and laws that allow the development of biofuels, having clear goals and objectives that contribute to the mission of diversifying the energy matrix;
- The promotion of instruments that allow the development of research, technologies, and training is an elementary part of the dissemination of biofuels [314].

The National Polytechnic Institute, SENER, and SEMARNAT also developed a normative proposal to incorporate biomethane into the natural gas network (Gasca, S. 2021) [315].

5.4.3.2 Social contributions

5.4.3.2.1 Social benefits and participation

Considering the inherent benefits of implementing biodigesters, the participants were further inquired on their perspectives on how these technologies can contribute to social development and the importance of social participation.

They agreed that social participation is an essential part of the development and sustainability of any waste-to-energy project, even more considering that nowadays there is a confluence of society more concerned about the environment and clean energy means. Also, as a waste management issue, anaerobic digestion projects at a large scale should include society's participation since it can also directly contribute to poverty alleviation (*PPQMX20*).

The implementation of biodigesters could offer many benefits: currently, the organic fraction is not valued by the garbage pickers, which could potentially generate new jobs (*PPQMX22*). It can also reduce the health issues arising from the contamination caused in landfills and dumpsites and lessen the expenses of managing this waste in a sanitary landfill (*PPQMX22*).

Furthermore, it was also pointed out by *PPQMX18* that during the installation of the projects, to the extent that training, and education are increased, the social license will be sustainable. New project developments will also help increase job opportunities, both in the development of technology and in the operation of these plants, eventually contributing to social development and creating better working conditions for the waste workers.

PPQMX19 also commented that social inclusion is not essential for the project design phase, stating that social inclusion in planning and design often raises more problems than solutions. Thus, society must be considered an opinion more than having direct involvement during these initial faces. In brief, according to the specialist, society participation must be not for a definition of the project but its authorization.

5.4.3.3 Environment and sustainable use of natural resources

Arable land occupation, forest degradation, biodiversity impacts are some of the possible environmental impacts that biofuel developments (mainly first generation) can cause. The expansion of bioenergy projects many times disregarded these environmental impacts in the expansion of bioenergy projects. It was asked to the specialist what could be done to include this precept in the current regulations and mitigate these impacts.

In the case of Mexico, this problem is not yet evident since no land, or very little, is used to produce bioenergetics (*PPQMX19*); excepting the production of biodiesel with palm oil, for example, or small producers of biogas with cactus in the state of Michoacán, by Nopalimex Company (*PPQMX21*). As agreed by many of the respondents, these practices should be restricted. The laws limiting this are forestry and agricultural regulations, where the preference must be for food growing and not energy. *PPQMX18* suggests that exclusion zones must be established to reduce any possible environmental impact in the areas of operation and establish regulations with a life cycle approach, ensuring the sustainability of the activity. These restrictions are yet to be emphasized in the legislation, and the Secretary of Agriculture must deal with it. Fields should always be preferred for growing food, not energy (*PPQMX19*), and bioenergy obtained from residues and not new croplands (*PPQMX22*).

5.4.3.4 Energy market

5.4.3.4.1 New financial incentives to foster the creation of biogas projects

As agreed by all the respondents, for the possible inclusion of biogas in the energy market and as a nutrient source, new financial incentives must be created considering the current conditions. In that regard, this questionnaire asked the respondents to develop on how this can be achieved. They mentioned the following:

- The development of this technology must be allowed, giving incentives, and favoring the market. These incentives could be focused on reducing taxes and facilitating market access to the biodigester industries. These tax cuts could be temporary, e.g., during the first five years of a project (*PPQMX19*);
- These incentives must be addressed to municipalities, farmers, or investors, giving access to credit from development banks (such as Banobras) with preferential rates for creating environmental and social benefits (*PPQMX18*). The previously mentioned CETEL credits (section 5.4.3.1.2) could be such a tool.
- Carbon credits could be obtained from the carbon markets, considering that currently, there is excellent demand from transnational companies (*PPQMX23*).
- Municipalities must first comply with the law to obtain these incentives. There must be a greater diffusion of this type of program because stakeholders and the public, in general, often do not know how to obtain the projects' financial funds (*PPQMX22*).
- Another mean is to accelerate depreciation schemes for the purchase of this type of equipment (*PPQMX18*);
- Also, new market rules must be established to have fair competition (*PPQMX23*). E.g., currently, in Mexico City, the zero-waste program has several edges that have not allowed the development of the bioenergy industry (*PPQMX19*).
- For the administration of these financial incentives and normative a government, the figure could be created to support all projects that have to do with biogas sanitation (*PPQMX20*).

5.4.3.4.2 Biomethane vs. diesel, gasoline, and ethanol

Including biogas and biomethane as fuel into the country's energy matrix is a real opportunity. Nevertheless, it competes with gasoline, diesel, and ethanol as an urban transportation fuel, heavy load trucks, and electric vehicles. To further understand its actual viability, one more question enquired the specialist on whether biomethane could potentially replace other transportation urban fuels and how this could be achieved.

The responses received by *PPQMX19* and *PPQMX23* mentioned that this decision must be left to the free market with an even floor; and thus, defined by demand. Quality, quantity, and price are essential factors for bioenergetics to compete. Therefore, as one of the respondents (PPQMX18) mentioned, if biomethane is encouraged, there should be more investment in training, research, and development. These incentives would allow the technological learning curve to advance faster and thus compete with other bioenergy technologies. For this purpose, it is worth continuing to channel resources and subsidies focused on research and development.

Some of the advantages of biomethane that could inherently make it more competitive, according to the interviewees, are the following:

- Per unit of biomass, biogas is one of the best biofuels; for example, there is more availability of organic material than material to generate biodiesel (*PPQMX20*).
- Biodiesel technologies are more complex (*PPQMX20*);

- Bioethanol or biodiesel technologies are currently based, with few exceptions, on first-generation biofuel sources (*PPQMX21*);
- Biomethane prices are becoming more competitive than gasoline and diesel (*PPQMX23*);

According to one of the interviewees (*PPQMX23*), the actual feasibility of biomethane in the country resides in the potential to replace some natural gas and diesel functions. For this, biogas could potentially go to isolated supply or distributed generation, not by the installed natural gas pipeline but by virtual pipelines. The current national regulation for natural gas could serve as a base for a new biogas regulation, which is still missing. Also, as the specialist mentions, biogas could serve as a vehicle fuel, as gasoline is now an elastic commodity. If its price rises, there are options to replace it, where biomethane has an opportunity.

It was also pointed out that the production of electricity in CHP stations through biogas technologies could help municipalities supply some of the electricity used (since it represents the second most relevant expense of municipalities). However, the sale of biomethane to supply the functions of natural gas (especially as a vehicle fuel) is currently more profitable *(PPQMX23)*. Also, the recent reform to the Electric Industry Law, recently released in March 2021, significantly impacts a possible electricity supply to municipalities since it favors the electricity coming from CFE (*PPQMX23*). There is currently an intense debate on this reform's advantages and disadvantages, which should be further studied.

On the other hand, as pointed out by one of the specialists (*PPQMX22*), something that must be considered is that biomethane cannot meet the demand for all vehicles in the country; and the transport sector is currently leaning more towards the use of electrical energy and hybrid cars. Additionally, the national government, in turn, is supporting the use of nonrenewable fuels, which also results in competitive disadvantages for biogas.

5.5 Policy proposals; guideline tables

Hereafter the research presents the policy guidelines which portray the current situation of each of the studied concepts. These summarize the detected current issues and challenges and the chances and opportunities for implementing AD technologies (and more specifically, DAD technologies) for both countries. The results presented are according to the literature review and the interviews with specialists. It is essential to highlight that these may not be the only existing challenges and opportunities, but rather the ones detected in this study through the interviews and, to less extent, secondary data analysis. From then on, recommendations were drawn for the guidelines and political actions to foster these technologies. Thus, this intends to identify the current situation and issues firsthand and propose practical and viable policy recommendations accordingly.

5.5.1 Policy guidelines & recommendations

The following guideline tables from interviews with researchers, stakeholders, and public policy specialists present the challenges and reasons for the still scarce implementation of DAD projects. This research section also presents the detected possible benefits and opportunities to install dry biodigesters to treat the OFMSW offered by these technologies for each sector, followed by the policy recommendations to attend these opportunities.

For the policy recommendations, this research attempts to emphasize realistic suggestions or proposals that can be politically viable and part from the following set of criteria: (1) Benefit society at individual, community, and national levels; (2) are publicly and practically acceptable; (3) harmonize with current legislation and not become an obstacle to other priority reforms; (4) are timely; and (5) do not imply vast amounts of money. The relevance and viability of each recommendation rely on complying with these precepts.

These new reforms or policy actions also must have enough support and no opposition from stakeholders to be politically feasible. The diverse sectors, stakeholders, and political actors must negotiate and agree to implement a particular policy. Regarding their cost efficiency, it shall also be considered the reforms that could be economically feasible, demonstrating that while money needs to be spent presently, it will save considerable amounts of public expenditure in the future. Additionally, a policy recommendation may have an enormous independent impact if it fits with an existing strategy, program, or legislation.

The actual viability of the policy recommendations here stated, and their robustness depends on the criteria mentioned above, also recognizing that many times “there are some difficulties when moving from theory to practice”. Even when the implementation process may present other challenges and not be easy, the results of these policy changes shall be satisfactory [316].

Hence, developing the recommendations from the interviews to public policy specialists helped to add to the robustness of the research considering that these officials are aware firsthand of the specific conditions of public administration for each case. They assume that features, tricks, and other intricacies are often not visible to the academic field.

The targeted audience of the following results is mainly decision-makers such as local authorities, city or district councils, ministers, a parliamentary committee of other civil servants in government departments, researchers, and the public. Both countries' response was often integrated and regarded for the other country's asseverations, considering the similarities in their policies and state of technology development.

The objectives of each of the stipulated policy recommendations shall be orientated, as CARDI (2012) [316] suggests, towards one or more of the following intentions: (a) Introduction of new legislation; (b) Changes to existing laws; (c) New governmental strategy; (d) Change in the direction of an existing strategy; (e) Improve an existing policy or service, and (f) Draw attention to a local issue such as planning transport or other public services.

“A policy recommendation is a simply written policy advice prepared for some group or person that has the authority to make or influence policy decisions... Policy recommendations are the key means through which policy decisions are made in most levels of government.” [316]

Topic	Waste Management	
Subtopic	*Landfilling and dumpsites*	
	Brazil	**México**
Current situation and Challenges	• Considering the vast amounts of available land, waste disposal in landfills or dumpsites is still the most competitive waste treatment solution, despite the waste of resources and energy. • These practices occupy large land extensions to process residues; • Landfills and dumpsites present environmental pollution and health risks; especially to the most vulnerable populations;	• Considering the vast amounts of available land, waste disposal in landfills or dumpsites is still the most competitive waste treatment solution, despite the waste of resources and energy. • Sanitary landfills are still seen as the optimal option for OFMSW treatment. • These practices occupy large land extensions to process residues; • Landfills and dumpsites present environmental pollution and health risks; especially to the most vulnerable populations; • Most municipalities do not charge for waste disposal (therefore, there is no money to invest in new technologies), and the rates are meager when there are. • Garbage collectors and cleaning workers' unions are sometimes obstacles to avoiding landfilling and automatizing or improving the MSW management systems. In many cases, municipalities want the concessionaires (when there are) to absorb the cost of the unions, which they do not do because it is expensive; therefore, the city majors tolerate "pepenadores".
Opportunities	• Value the diverse materials in waste. Only the non-reusable garbage must be sent to sanitary landfills; • The implementation of new waste treatment technologies that are more environmentally appropriate and bring benefits to society. • Anaerobic digestion is an optimal solution for the treatment of OFMSW and many other agricultural residues.	• Value the diverse materials in waste. Only non-reusable garbage must be sent to sanitary landfills; • The implementation of new waste treatment technologies that are more environmentally appropriate and bring benefits to society. • Anaerobic digestion is an optimal solution for the treatment of OFMSW and many other agricultural residues. There are millions of tonnes of organic waste in the country; it is just a matter of proper management. • Implementing anaerobic digesters has to go to waste treatment, considering its primary function is sanitation rather than energy production.

Recommendations	• Comply with the policies to avoid landfilling and foster the harnessing of materials or energy in the waste. • Give support to municipalities, or consortia of municipalities, carried out by the federation and states for adequate treatment of MSW. • Increase surveillance to prohibit irregular disposal (dumpsites). • An essential action is the development of a strategy to implement waste generation reduction goals. • Carry studies to know and redesign the rejected fraction for its reduction. • Promote the implementation of anaerobic reactors to treat the residue sludge derived from wastewater treatment plants.	• Develop the existing policies to avoid landfilling and foster the harnessing of material or energy in the waste. • Increase surveillance to prohibit irregular disposal (dumpsites). • An essential action is the development of a strategy to implement waste generation reduction goals. • To develop a specific public policy for MSW, with biogas generation, giving support to municipalities or consortia of municipalities by the federation and states. • To set higher and significant monetary charges for the disposal of waste in dumps and landfills; so that with the taxes, investments can be made in biodigestion technologies. • Carry studies to know and redesign the rejected fraction for its reduction; • Promote the implementation of anaerobic reactors for the treatment of the residue sludge derived from wastewater treatment plants.

Topic	Waste Management	
Subtopic	*Source Segregation*	
	Brazil	**México**
Current situation and Challenges	• Misuse of the residues generated; • Difficulty in reusing or recycling residues due to their impurities content. • Lack of compliance with the law for the segregation of waste;	• Misuse of the residues generated; • Difficulty in reusing or recycling residues due to their impurities content. • Lack of compliance with the law for the segregation of waste;
Opportunities	• A source segregation system would ease and benefit the management, treatment, and disposal of wastes; and improve the treatment of MSW and its Organic Fraction within the cities. • Segregation of at least three fractions: organics, dry recyclables, and non-reusable garbage. • Source segregation brings minor impurities, significant quality of feedstock for recycling, socioeconomic benefits, among others. • Source segregation of residues is very relevant for the success of AD digestion technologies within urban spaces; for biogas generation and contaminant-free biofertilizers. For this, citizen participation is essential, in addition to the selective municipal collection.	• A source segregation system would ease and benefit the management, treatment, and disposal of wastes; and improve the treatment of MSW and its Organic Fraction within the cities. • Segregation of at least three fractions: organics, dry recyclables, and non-reusable garbage. • Source segregation brings minor impurities, significant quality of feedstock for recycling, socioeconomic benefits, among others. • Source segregation of residues is very relevant for the success of AD digestion technologies within urban spaces; for biogas generation and contaminant-free biofertilizers. For this, citizen participation is essential, in addition to the selective municipal collection.
Recommendations	• Implement more effective actions in the non-generation, reuse, and source segregation of MSW. • “Taxing sanctions” could be set for the disposal of organic waste in landfills. • Increase selective collection in the country aiming to meet the waste management hierarchy. • Develop and implement national and municipal waste source segregation plans or strategies to separate at least three fractions: organics, dry recyclables, and non-reusable garbage.	• Implement more effective actions in the non-generation, reuse, and source segregation of MSW. • “Taxing sanctions” could be set for the disposal of organic waste in landfills. • According to the national solid waste policies, increase selective collection to meet the management hierarchy. • National and municipal governments should implement waste source segregation plans or strategies to separate at least three fractions: organics, dry recyclables, and non-reusable garbage.

Topic	Dry Anaerobic Digestion	
Subtopic	*DAD Technical Aspects*	
	Brazil	**México**
Current situation and Challenges	• The country is in the process of adopting the technology, considering its complexity; • Low interest in the development of national technologies from stakeholders; • There is a lack of documentation on the analysis of the biogas markets; technical, economic, and environmental performance of the existing biodigesters´ companies. • Choice of materials to build the installations (metallic reactors seems to be a problem for the digestion of OFMSW since their treatment develops high temperatures); • High variability on the conditions, characteristics, and quantities of each substrate; • Lack of information on how much can DAD contribute to GHG mitigation; • Lack of technical knowledge and documentation (technology and biological processes); to install and maintain the process. • High operational costs; • Poor substrate homogeneity and lack of mixture; • Lack of compliance with the law;	• Low interest in the development of national technologies from stakeholders; • There is a lack of documentation on the analysis of the biogas markets; technical, economic, and environmental performance of the existing biodigesters´ companies. • Choice of materials to build the installations (metallic reactors seems to be a problem for the digestion of OFMSW since their treatment develops high temperatures); • High variability on the conditions, characteristics, and quantities of each substrate; adequate substrate characteristics and homogeneity; • There is a gap between research centers and the industrial sector in Mexico, missing the bridge and link to generate the knowledge and transform it into new technologies. • Lack of information on how much can DAD contribute to GHG mitigation; • Lack of technical knowledge and documentation (technology and biological processes); to install and maintain the process. • High operational costs; • Poor substrate homogeneity and lack of mixture; • Lack of compliance with the law; • Make the use of biomethane compatible with the vehicle industry, among others.
Opportunities	• Significantly contribute to reaching Brazilian GHG reduction goals; firstly, by the otherwise emitted CH_4, CO_2 and other gases by landfills; secondly, diverting fossil fuels to be used and saving the CO_2 emissions of standard electricity production methods or transportation means from the fuel replaced by biomethane. • Fewer mineral extractions and biofertilizers production.	• Significantly contribute to reaching Mexico GHG reduction goals; firstly, by the otherwise emitted CH_4, CO_2, and other gases by landfills; secondly, diverting fossil fuels to be used and saving the CO_2 emissions of regular transportation means from the fuel replaced by biomethane. • Fewer mineral extractions and biofertilizers production.

	• Further development of technologies and processes. In Brazil, the structural capacity and technical knowledge (still missing some aspects for DAD technologies) are already available to develop local technologies. • Keep the treatment as simple as possible. DAD is best for the solid waste fraction and does not have to be continuously fed. • DAD demands less water utilization through its biodigestion processes. • The size of DAD reactors can be 30% smaller than WAD processes, among other advantages of DAD systems. Others: • WAD systems could utilize adequate wastewater to co-digest it with solid residues, benefiting wastewater treatment and non-potable water usage.	• Invest in biodigesters for self-consumption through small projects. There is an increasing potential in small towns. • Further development of technologies and processes. • Successful biodigester pilot projects must be carried out to demonstrate the feasibility of these technologies. This successful pilot plants shall raise interest in the private sector which would be a key factor. Hence, not depending totally on the government. A private project with international support could be the example to follow, which would allow the market to be opened; • Keep the treatment as simple as possible. DAD is best for the solid fraction of the waste and does not have to be continuously fed. • DAD demands less water utilization through its biodigestion processes, • The size of DAD reactors can be 30% smaller than WAD processes, among other advantages of DAD systems. • WAD systems could utilize adequate wastewater to co-digest it with solid residues, benefiting wastewater treatment and non-potable water usage.
Recommendations	• Demonstrate the advantages of biodigestion for potential producers presenting information with technical quality. These technology promotions could be through technical seminars, such as ABiogas is carrying out. • Share successful cases with decision-makers; develop new pilot plants through research centers to further demonstrate that these technologies can be successful and thus disseminate them. • Once implemented, carry out professional management of the technologies, which is very important for the success and economic profitability of the projects. • Development of AD by dry route for solid organic residues, avoiding as much as possible the transportation of the substrates for long distances. • Expand DAD projects to the rural market.	• Demonstrate the advantages of biodigestion for potential producers presenting information with technical quality. These technology promotions could be through technical seminars, such as CNBiogas is carrying out. • Share successful cases with decision-makers; develop new pilot plants through research centers to further demonstrate that these technologies can be successful and thus disseminate them. • Generate a general report of the Anaerobic Digestion systems at a national and international level, including performance, materials, costs, equipment. • Once implemented, develop professional management of the technologies, which is very important for the success and economic profitability of the projects.

	• The risk of failing to manage an AD technology needs to be carefully considered since there have been cases when they do not reach viability.	• Development of AD by dry route for small volumes and local uses, avoiding as much as possible the transportation of the substrates for long distances. • Expand AD projects to the rural market. The development of biodigesters in small towns for self-consumption and small scale must be taken into account. • The risk of failing to manage an AD technology needs to be carefully considered since there have been cases when they do not reach viability.

Topic	Social contributions	
Subtopic	*Social benefits and participation*	
	Brazil	**México**
Current situation and Challenges	• General lack of knowledge, interest, and participation for the implementation of these systems. • High expectations and exigencies from the neighboring people when projects are to be installed. • Health impacts and risks by the current waste treatment methods. • There is still not enough training and education on the topic.	• General lack of knowledge, interest, and participation for the implementation of these systems. • High expectations and exigencies from the neighboring people when projects are to be installed. • Health impacts and risks by the current waste treatment methods. • Social inclusion in planning and design sometimes raises more problems than solutions. It is not essential for project design, only for authorization. • There is still not enough training and education on the topic.
Opportunities	• Biogas generation can be an agent for social development, especially for the informal sector and less advantageous people like garbage pickers. • Society can contribute to reducing the overall carbon footprint and health risks that traditional waste treatment methods cause. • Increase of job opportunities, both in the development of technology and in the operation of these plants. • Reduction of electricity and transportation costs for society. • Citizen participation is an essential part of the development and sustainability of any project. • Society needs to be more aware of the social and environmental impact that arises with waste generation. • Implementing biodigesters could offer many social benefits: currently, the garbage pickers do not value organic fraction, generating new jobs. It can also reduce the health issues arising from the contamination generated in landfills and dumpsites and lessen the expenses of managing this waste in a sanitary landfill.	• Biogas generation can be an agent for social development, especially for the informal sector and less advantageous people like garbage pickers. • Society can contribute to reducing the overall carbon footprint and health risks that traditional waste treatment methods cause. • Increase of job opportunities, both in the development of technology and in the operation of these plants. • Reduction of electricity and transportation costs for society. • Citizen participation is an essential part of the development and sustainability of any project. • However, society must be considered during the planning and authorization phase, rather than directly involved with the project design. • Implementing biodigesters could offer many social benefits: currently, the garbage pickers do not value organic fraction, generating new jobs. It can also reduce the health issues arising from the contamination generated in landfills and dumpsites and lessen the expenses of managing this waste in a sanitary landfill.

Recommendations	• Involve society's participation, mainly to create demands for implementing these projects and planning the project. • Develop educational policies to raise consciousness for the adequate disposal of residues at a societal level. • Create means to improve the public's perception, making information accessible to facilitate the interest of individuals for the treatment of urban organic waste through anaerobic digestion, and understand all the benefits obtained with this proper waste treatment method.	• Include more participation of society and understand the utility regulatory role that it represents. • Develop educational policies to raise consciousness for the adequate disposal of residues at a societal level. • Create means to improve the public's perception, making information accessible to facilitate the interest of individuals for the treatment of urban organic waste through anaerobic digestion, and understand all the benefits obtained with this proper waste treatment method. • Formally consider the unions of garbage pickers, "pepenadores", and cleaning workers in the governance network so that they can be adequately treated and remunerated.

Topic	Economic factors	
	Brazil	**México**
Current situation and Challenges	• High investment costs are sometimes inaccessible and cause economic unfeasibility since the technology needs to be imported. • High operational and maintenance costs. • One of the main challenges is finding adequate investment funds for long-term and attractive contracts at the same time. • Lack of interest of some stakeholders such as investors or private companies due to the financial risks; • There is still no commercial production of DAD technologies.	• High investment costs are sometimes inaccessible and cause economic unfeasibility since the technology needs to be imported. • High operational and maintenance costs. • Find adequate investment funds for long-term and attractive contracts at the same time. • Lack of interest of some stakeholders such as investors or private companies due to the financial risks; • Lack of governmental incentives for the development of national technologies. • There is currently considerable academic development but little technological development in the country; therefore, these technologies must be imported. • There is still no commercial production of DAD technologies.
Opportunities	• With the development of national or local technologies, local suppliers can offer a competitive advantage in costs and technology adaptation. • Generate considerable revenues from energy and fertilizer generation.	• With the development of national or local technologies, local suppliers can offer a competitive advantage in costs and technology adaptation. • Generate considerable revenues from energy and fertilizer generation.
Recommendations	Economic viability could be achieved by stipulating that there is already enough demand and supply opportunities. For this to happen, it is necessary: • To develop local technology products suitable for the Brazilian realities, adapted to the conditions and substrate characteristics. • To reduce system production costs. • Governmental incentives and benefits might be encouraged to start the projects. • Improve the control of processes to produce energy at competitive costs; • Include and encourage the participation of the private sector through public-private agreements in projects for the	Economic viability could be achieved by stipulating that there is already enough demand and supply opportunities. For this to happen, it is necessary: • To develop local technology products suitable for the Mexican realities, adapted to the conditions and substrate characteristics. • To reduce system production costs, developing viable technologies locally. • Governmental incentives and benefits might be encouraged to start the projects. • Learn how to control the processes properly and produce energy at competitive costs; • Include and encourage the participation of the private sector through public-private agreements in projects for the separation,

	separation, reuse, and recycling of waste and create new incentives for the development of biodigesters. • Develop an understanding that the investment is recovered, and profits are gained in long-term periods. • Accelerate depreciation schemes for the purchase of this type of equipment. • To clear revenues from both biogas/biomethane and the quality digestate (organic fertilizer). • Sanctions for the deposit of organic waste in landfills shall raise funds to encourage the utilization of AD technologies. • Developing a value chain would stimulate funding agencies, and the expansion of product distribution networks. • Create specific credit lines for new biogas projects and working capital from the diverse ministries. • Carbon credits could be obtained from the carbon markets, considering that currently, there is excellent demand from transnational companies.	reuse, and recycling of waste and create new incentives for the development of biodigesters. • Develop an understanding that the investment is recovered, and profits are gained in long-term periods. • Accelerate depreciation schemes for the purchase of this type of equipment. • To clear revenues from both biogas/biomethane and the quality digestate (organic fertilizer). • Sanctions for the deposit of waste in landfills shall raise funds to encourage the utilization of AD technologies. • Developing a value chain would stimulate funding agencies, and the expansion of product distribution networks. • For the administration of new financial incentives and normative, a government figure could be created to support and manage all projects that have to do with biogas sanitation. • There must be a greater diffusion of the current funding programs because stakeholders often do not know how they can obtain the financial funds of the projects. • Carbon credits could be obtained from the carbon markets, considering that currently, there is excellent demand from transnational companies. • Develop and be more open to economic instruments, which will motivate the implementation of biodigesters due to the economic benefits. Experience has shown that attempts with command-and-control mechanisms have not proficiently worked, mainly due to their financial dependence and low competitiveness.

Topic	Environmental impacts	
	Brazil	**México**
Current situation and Challenges	• Arable land occupation, forest degradation, biodiversity impacts are some of the possible environmental impacts that biofuel developments (mainly first generation) can cause.	• Arable land occupation, forest degradation, biodiversity impacts are some of the possible environmental impacts that biofuel developments (mainly first generation) can cause.
Opportunities	• Include this precept in the current regulations and mitigate these impacts. • New stipulations and exclusion zones must be established to reduce the environmental impact in the areas of operation, production of biogas and other biofuels, avoiding any exploitation of forest or other new lands. • Biogas projects should be kept as an accessory for rural producers, agroindustry, and the food industry, mainly to treat organic wastes and residues. • Fields shall always be preferred for food growing and not energy production.	• Include this precept in the current regulations and mitigate these impacts. • New stipulations and exclusion zones must be established to reduce the environmental impact in the areas of operation, production of biogas and other biofuels, avoiding any exploitation of forest or other new lands. • Biogas projects should be kept as an accessory for rural producers, agroindustry, and the food industry, mainly to treat organic wastes and residues. • Fields shall always be preferred for food growing and not energy production.
Recommendations	• Incorporate in the current legislation measures and restrictions to use new areas for exploitation for bioenergy generation and restrict the utilization of organic wastes and residues. • Establish regulations with a life cycle approach, which ensures the sustainability of the activity. • 1st generation biodigesters could be allowed just when certain conditions are applied, for example, to rotate the plantations, protect the soil, among others. • Recognize the production and use of biogas as an environmental service lawfully;	• Incorporate in the current legislation measures and restrictions to use new areas for exploitation for bioenergy generation and restrict the utilization of organic wastes and residues. • Establish regulations with a life cycle approach, which ensures the sustainability of the activity. • 1st generation biodigesters could be allowed just when certain conditions are applied, for example, to rotate the plantations, protect the soil, among others. • Recognize the production and use of biogas as an environmental service lawfully;

<table>
<tr><td>Topic</td><td colspan="2">Energy Markets</td></tr>
<tr><td>Subtopic</td><td colspan="2">Biogas Markets and networks</td></tr>
<tr><td></td><td>Brazil</td><td>México</td></tr>
<tr><td>Current situation and Challenges</td><td>Lack of a specific regulatory framework for biogas/biomethane market;
Lack of infrastructure for biogas production and distribution;
Still low competitiveness of prices of biogas energy with other energy sources.
Some of the present challenges to implementing biogas projects in the national energy matrix are the development and adaptation of the technology, technology, and operational costs and the lack of interest from stakeholders.
Competitiveness of costs and price of biogas energy with other energy sources; decrease in regulatory costs;
Natural gas is often very competitive since it is given even for free in some regions that have oil platforms. These due to their regulated flare limits;</td><td>Lack of a regulatory framework for biogas/biomethane market;
Lack of infrastructure for biogas production and distribution;
Still low competitiveness of prices of biogas energy with other energy sources;
There is no market for biofuels in the country.
Bioenergy and biogas have lagged in the last places of clean energy in the country.
Currently, biogas must open its way by itself because the government does not support it.
As renewable energies, electricity from wind and solar sources is currently more competitive in the country.
The national government, in turn, is currently supporting the use of fossil fuels, which also brings competitive disadvantages to biogas.</td></tr>
<tr><td>Opportunities</td><td>Expansion of the biogas consumer market.
Availability and adaptation of the existing natural gas equipment.
Expansion of services for the biogas sector.
Expansion of the gas pipeline network.
Demand for diesel oil by public transport services (such as garbage trucks and urban buses), operated mainly by City Halls, could be supplied by the biomethane produced with the urban and rural OSW.
It is important that biomethane is differentiated from natural gas and recognized for its gas properties with other advantages such as reducing emissions.</td><td>Inclusion of biodigesters as an energy and nutrient source.
Expansion of services for the biogas sector.
Expansion of the gas pipeline network.
Biogas technologies might be costly (mainly due to the cost of the technologies), but it provides stability in the energy network.
The development of CEMIE-Bio with its five clusters was a great initiative to stimulate research on the subject.
Demand for diesel oil by public transport services (such as garbage trucks and urban buses), operated mainly by City Halls, could be supplied by the biomethane produced with the urban and rural OSW.
The production of electricity in CHP stations through biogas technologies could help municipalities supply some of the electricity used (since it represents the second most crucial</td></tr>
</table>

		expense of municipalities). However, the sale of biomethane to supply the functions of natural gas (especially as a vehicle fuel) is currently more profitable.
Recommendations	• An appealing path can be to inject biomethane into the gas network, making mandatory a particular percentage mixture with natural gas (such as the current obligations for ethanol added to gasoline or biodiesel into diesel); however, it is not a simple political path. • Articulate and integrate the biogas markets, investing in the expansion of gas networks and services for biogas. • Create new incentives for the more significant expansion of biodigesters. E.g., incentivize electricity generation with biogas. • Auctions for specific electricity and biomethane from biogas. There would be no need for subsidies because it encourages the development through the market; • Develop an environment for remunerating the generation of biogas as a renewable energy service. • To have less bureaucracy for the market strategies for biogas projects.	• The development of this technology must be allowed giving incentives and favoring the creation of a biofuels market. • Create a new law for the regulation, articulation, and foster of a biofuel market; for this, new market rules must be established to have fair competition. • Incentives must be focused on reducing taxes and facilitating market access to the biodigester industries. These tax cuts could be temporary, e.g., during five years; • Also, creating financial incentives for farmers, giving access to credits from development banks with preferential rates due to their contribution to environmental and social benefits; • Invest in research, technological development, and innovation to make processes more competitive. For this purpose, it is worth continuing to channel resources for subsidies to the energy sector, focused on research and development and their projects, e.g., CEMIE-Bio. • Amend the regulations of the so-called Clean Energy Certificates (CEL´s) for greater participation of biogas in the national energy matrix. • The creation of CETEL´s would allow that thermal energy technologies compete with each other and not against different types of energies. • Energy should not be the primary driver for implementing biodigesters but the waste treatment and the recovery of nutrients as organic fertilizers. • Biogas could potentially go to isolated supply or distributed generation, not by the installed natural gas pipeline but by virtual pipelines.

Topic	Energy Markets	
Subtopic	*Biomethane*	
	Brazil	**México**
Current situation and Challenges	• The Biomethane market as a fuel for heavy load trucks in Brazil is currently expanding. • Biomethane is not a single measure to solve the problem of fossil fuels exploitation, considering the existence of other biofuels such as ethanol or hydrogen. Hence, it should be applied where it is suitable and viable.	• Biomethane developments are only in an experimental phase in the country. • Biomethane production cannot meet the demand for all vehicles in the country, and the transport sector is currently leaning more towards the use of electrical energy and hybrid cars. • Biomethane is not a single measure to solve the problem of fossil fuels exploitation, considering the existence of other biofuels such as ethanol, hydrogen, or electric cars. Hence, it should be applied where it is suitable and viable.
Opportunities	• Extend the use of biomethane for vehicle fleets; • Develop new technologies that can potentially use biomethane, such as motor cars and heat & power generators. • Biomethane has the opportunity to supply up to 53% of the 7.2 billion liters of diesel used by the agricultural sector in Brazil [304]. • Biomethane can replace it in fleets or vehicles that work with this bioenergy with similar chemical properties to natural gas. There would have to be a more robust system for its distribution. • There is an opportunity to create a policy for using biomethane as a fuel to replace natural gas (CNG) and diesel in vehicles, resulting in a direct incentive for investors to have a guaranteed return.	• Use of biomethane for vehicle fleets; • Development of new technologies that can potentially use biomethane such as fleet vehicles, cars, and heat & power generators; • Biomethane could be produced with the urban and rural OSW and supply the demand for diesel oil by public transport services (such as garbage trucks and urban buses). • The potential of biomethane in the country resides in its potential to replace natural gas and diesel functions. Some of the advantages of biomethane that could inherently make it more competitive than other fuels, according to the interviewees, are the following: • Per unit of biomass, biogas is one of the best biofuels; for example, there is more availability of organic material than material to generate biodiesel. • Bioethanol or biodiesel technologies are currently based, with few exceptions, on first-generation biofuel sources; • Biomethane prices are becoming more competitive than gasoline and diesel;

Recommendations	• Incentivize biomethane as an urban transportation fuel, considering its low carbon footprint and capacity to mitigate the environmental impacts caused by gasoline and diesel.	• Inclusion of biomethane as fuel into the energy matrix of the country. The free market should be allowed to create interest and participation in the private sector. • Regulate the inclusion of biomethane into the national grid. • Make the use of biomethane compatible with the vehicle industry; • Investment in the training of talent and research & development would allow the technological learning curve to advance faster and thus compete with other technologies.

Topic	Public policy	
	Brazil	**México**
Current situation and Challenges	• Public policy deficiencies: anaerobic digestion is addressed many times in the current laws but is mostly just an organic waste treatment method and not in a relevant manner. • There is not enough concern of environmental issues of decision-makers; • Lack of regulation for the enforcement of the implementation of AD; • Stakeholders, in many cases, do not attend or comply with the existing legislation and regulations. • Not enough commitment from local authorities, for example, to reduce the high taxes on imported equipment. • The time to foster and implement these technologies is sometimes too long to be of genuine interest to certain politicians. • There is much bureaucracy for the development of biogas projects. • On many occasions, federal waste management and bioenergy regulations are not applied, and there are no penalties for non-compliance. • Information asymmetry, where some stakeholders have more information than decision-makers.	• The government has refused to subsidize biogas projects. • Public policy deficiencies: anaerobic digestion is addressed many times in the current laws but is mostly just an organic waste treatment method and not in a relevant manner. • There is not enough concern of environmental issues of decision-makers; • Lack of regulation for the enforcement of the implementation of AD; • Stakeholders, in many cases, do not attend or comply with the existing legislation and regulations. • Not enough commitment from local authorities, for example, to reduce the high taxes on imported equipment. • The political rotation at the municipal, state, and federal levels is one more of the factors that have inhibited the effective implementation of these programs. • The time to foster and implement these technologies is sometimes too long to be of genuine interest to certain politicians. • AD technologies compete with policies that promote other systems for the generation of energy, such as wind and solar; • AD projects that have been developed are not given continuity and, in many cases, they were simple technologies that mostly did not work proficiently in the long term; • A new regulation focused on biogas already began, but it did not advance further due to bureaucracy. • On many occasions, federal waste management and bioenergy regulations are not applied, and there are no penalties for non-compliance.
Opportunities	• Promotion of events that allow the exchange of practical, technical, and economic knowledge, bringing together specialists, public authorities, market developers, and potential investors.	• Promotion of events that allow the exchange of practical, technical, and economic knowledge, bringing together

	• More awareness could be raised to disseminate the technology and demonstrate the viability of AD with some program or political strategy. • Biogas from organic wastes can be a relevant governmental asset; new regulations are necessary for their actual implementation.	specialists, Public Authorities, market developers, and potential investors. • More awareness could be raised to disseminate the technology and demonstrate the viability of AD with some program or political strategy. • Biogas from organic wastes can be a relevant governmental asset; new regulations are necessary for their actual implementation.
Recommendations	Amendments and inclusions to the current legislation should be proposed, such as: • Prepare and implement new specific regulations and policies to develop more precise and coercive measures for the adequate treatment of OFMSW and sewage sludge through biodigesters; as well as the regulations for the use of biogas and biomethane; • Implement the principles of circular economy as an adaptation to the existing legislation. • Increase surveillance to prohibit irregular disposal (dumpsites). • Include co-digestion processes in the legislation. • Implement DAD pilot projects (or new developments) to give more clarity to decision-makers. • Create transversality and harmonization of all the existing policies pursuing the same results. • Promote practical projects where companies are associated with universities that seek to solve problems. • Develop a biogas federal regulatory framework providing a guide for biogas policies, competencies, incentives, and resources for their implementation; • Carry out auctions for specific electricity production from biogas; • Create specific credit lines for new biogas projects and working capital. • Develop an environment for remunerating distributed energy generation services; • The electricity generated with OFMSW must be valued; • Recognize the production and use of biogas as an environmental service lawfully;	Amendments and inclusions to the current legislation should be proposed, such as: • Prepare and implement new specific regulations and policies to develop more coercive measures for the adequate treatment of OFMSW and sewage sludge through biodigesters; as well as the regulations for the use of biogas and biomethane; • Implement the principles of circular economy as an adaptation to the existing legislation. • Increase surveillance to prohibit irregular disposal (dumpsites). • Include the co-digestion processes in the legislation. • Implement DAD pilot projects (or new developments) to give more clarity to decision-makers. • Create transversality and harmonization of all the existing policies pursuing the same results. • Stimulate the development of capacity and knowledge. • Promote practical projects where companies are associated with universities that seek to solve problems. • Develop a biogas federal regulatory framework providing a guide for biogas policies, competencies, incentives, and resources for their implementation; • Carry out auctions for specific electricity production from biogas; • Create specific credit lines for new biogas projects and working capital. • Create a specific policy for fleet methanization, mainly for large urban centers with the use of locally generated biomethane; • Develop an environment for remunerating distributed energy generation services.

	• Reduce the political bureaucracy for the market strategies for biogas projects. • Form a national biogas policy, state plans could be derived, which can adapt to the particularities of each state. This could be implemented through certain state agencies to provide more security for investors and more harmonious regulations between the state and the federation. • Create a specific policy for fleet methanization, mainly for large urban centers with the use of locally generated biogas; • Create specific policies for the treatment of MSW and sewage sludge, with the generation of biogas in the treatment of the organic fraction, and the use of the biogas generated (thermal, electric, and transport); • Create a specific biogas commission at the federal level that includes several ministries in a more transversal way.	• The electricity generated with OFMSW must be valued; • Recognize the production and use of biogas as an environmental service lawfully; • To be effective, developing a new regulation focused on biogas must enter through a sector head, SENER or SEMARNAT. • More policies must be implemented at the municipal level to be more directly complied with. • Applying stricter means to enforce the law compliance determinately is essential. • Create a new national normative (NOM) for the treatment of digestate, including specifications for the diverse types of wastes and conditions of the various organic wastes. • Release governmental funds to develop demonstration projects that successfully portray state-of-the-art technologies. The primary intention is to foster the involvement of the private sector, which would play a key role in allowing the market to open. Programs can be generated where the organic fraction is granted to private companies.

Table 24: Challenges and opportunities for improvement of some Policies in Brazil

Policies	Challenges	Opportunities & recommendations
PNRS	• Technical, economic, and market challenges inhibit biogas projects' development from treating solid organic residues.	• Include the guidelines in the regulation to improve energy recovery from MSW. • Create strategies to overcome the current technical, economic, and market challenges. • Define the mechanisms to enable the agencies to monitor and enforce the compliance of the law and respect the waste treatment hierarchy. • It could encourage the consortia between municipalities, which can be developed to manage waste between several cities. • Financial efficiency shall also be considered for the private sector. • Design routes for the recovery of organic waste and energy public use, such as electricity generation and compensation in public buildings and biomethane production for urban bus fleets.
RenovaBio	• With numerous projects being supported for ethanol and biodiesel, biogas is still the least fuel attended. • This law is restricted to biomethane marketed for use in transportation. • If a plant produces biomethane for its fleet, it does not generate CBIOs, unless it manages a sales process. This fact makes the CBIO more expensive, the operation more complex, and transaction costs increase. • The cost for monitoring is relatively high, which restricts the project's eligibility for the large-scale production and commercialization of biomethane. • Due to the current pandemic situation, The Ministry of Mines and Energy has reduced RenovaBio targets, which has resulted in a considerable reduction of biofuels production (Specially ethanol).	• This law could incorporate and encourage the use of the biogas already produced in many landfills by establishing progressive goals for the use of biogas in vehicles and gas distributors. • It could further encourage biogas projects by improving conditions for the generation and commercialization of CBIO´s, focusing on small and medium biogas producers, who cannot afford the Program´s costs. • It could include a new mandate to encourage the generation of credits either by direct or indirect subsidy. • It could diversify biogas utilization other than transportation, such as electricity production or domestic use. • The government could create robust programs to develop projects, activities, and actions to implement this law.
PNE	• Biogas is often included in the Plan; however, it is mentioned very generally, lacking reliable data. As if it was a technology that is just starting. • Information asymmetry, as if they do not have enough information of this energy source.	• Include actual data and goals, considering that Brazil already gained knowledge on the topic with the more than 500 biodigestion plants throughout the country and many successful cases.

	• Natural gas is still considered an energy source for future developments, and many times it does not leave room to be substituted by biogas technologies.	• The Plan can consider much more biogas technologies, according to the vast information that has been already developed by institutions such as ABiogas, CIBiogas, or EPE, among others. • Negotiate with the Ministry of Energy and EPE a significant contribution of biogas in the energy matrix. • Adapt institutions, regulations, and market arrangements to enhance the use of biogas and biomethane in the energy transition [304]. • Articulate energy policies with Science, Technology, and Innovation policies [304]. • Development of a roadmap for the use of biomethane [304].
PDE	• It only mentions the possible contributions that biogas can bring to the energy matrix in Brazil.	• The PDE should improve the scenarios for biogas, considering that it has great potential, where currently only 2% of that potential is exploited. • Present higher scenarios, including a more significant portion of biogas in the country's energy matrix. For instance, the Plan mentions that Brazil can deliver 7.1 billion m^3/year in 2029 just from the biodigestion of vinasse and filter cake. • Present more specific information and data about the potential of the biogas processes considering its additional attributes, so it is not only energy but a reduction of emissions, fertilizers production, and social benefits.
Others	• Lack of diffusion of the two new public calls to open biogas technologies to the local markets: (1) Tropicalization of technologies, and (2) Consolidation of demonstrative units of biogas and biomethane.	• Strength up and diffuse these new public calls to propagate them to other regions of the country.

Table 25: Challenges and opportunities for improvement of some Policies in Mexico

Policies	Challenges	Opportunities
General Law for the Prevention and Integral Management of Solid Waste	• Landfills are still the solution considered as optimal by law. • After the new reform on January 8th, 2021, there is still a lack of methodology or strategy to make waste to energy a reality.	• Include the generation of energy from organic waste in the existing law. The new reform in January 2021, for the first time, stipulates that solid waste can be used for energy recovery. • Define and specify what wastes can be transformed into energy. • To strengthen regulation and forcing the treatment of waste.
The General Law On Climate Change	• This law does not directly support the development of biogas technologies. • It is stipulated that each municipality must develop a Municipal Climate Action Plan (PACMUN); however, this Plan is usually lagging or even not contemplated in municipal development plans.	• Give all the responsibility to a single Institution for bioenergies and do not distribute it. • Regulate to invest in research and development from both the public sector and venture capital funds. • Also, the great value of the digestate to enrich soils must be contemplated in this law. • Enforce and or incentivize the creation of a Municipal Climate Action Plan (PACMUN).
Transition Strategy to Promote the Use of Cleaner Technologies and Fuels/ Intersecretary Strategy for Bioenergetics	• These regulations do not consider bioenergy technologies sufficiently to meet clean energy goals and the energy efficiency goal. • Those strategies focus on wind and solar energy, and they have not contributed to fostering biogas.	• Include bioenergy as a proficient means to contribute to meeting the clean energy goals of the country. • Have a diversified portfolio of renewable energies and do not concentrate just on few technologies.
The Law for the Promotion and Development of Bioenergetics	• This law obeys a regulatory logic that proposes to promote requirements for command and control, restricting the propagation of bioenergetics.	• Promote the creation of infrastructure to produce bioenergetics, creating incentives for the development of this Industry.
Electric Industry Law	• Fossil fuel energy is favored.	• Biogas can contribute to the production of electricity in CHP stations, which could help municipalities supply some of the electricity used since it represents a vital expense source.
Others	• Lack of direct governmental incentives to renewable thermal energy projects.	• Firstly, it is recommended to carry out a market analysis. Creating the CETEL´s could work and be an effective initiative to open and stimulate the bioenergy market as a solid contributor to suffice the thermal energy demands. If CETEL´s results are viable, there must be an official control body to regulate and monitor these specific certificates.

5.6 Next steps

For a more detailed feasibility study of each of the opportunities and recommendations here stated, a PESTEL analysis is suggested, which focuses on how political, economic, social, technological, environmental, and legal factors affect the feasibility of a policy option. This would precisely detect the pros and cons of each political action to determine what is feasible. It might also be relevant to develop a budgetary feasibility analysis to determine the actual financial viability of the recommendations.

Accordingly, a state plan for the integral management of the OFMSW could be developed, which can holistically contain a set of objectives, goals, programs, projects, and activities for relevant and successful management of the organic wastes within the cities.

5.7 Key findings

In Brazil, implementing biogas and biomethane through diverse strategies has prevailed, expanding, and gaining inertia. The policies are aligned with the trend to implement low-carbon energy systems. Biogas participation is moderately increasing, and there is a horizon of opportunities to expand its contribution to the energy matrix. It is currently having a stimulus in its expansion through diverse public and private strategies. The primary sanitation sector is the main biogas generator, and electricity is the main product.

In Mexico, since 2005, there have been initiatives and attempts to implement anaerobic digestion projects throughout the country. However, these governmental and financing programs have not achieved the expected results on more efficient biodigesters implementation. The situation derives from several factors, such as (1) Previous policies were focused just on small plants designed for self-consumption; (2) Knowledge of biodigestion was low, and there was little connection to diverse stakeholders; (3) It was not financially appealing, and technologies demanded considerable maintenance costs; (4) Lack of specific policies to allow the further development of this type of project; (5) The cost of the technologies demanded considerable subsidies.

Currently, both countries present some challenges that hinder the implementation of such projects at a constant rate. In general terms, some of these challenges are presented, according to this research findings, due to landfill and dumpsites overuse; lack of waste segregation systems; lack of knowledge or interest in AD technologies; low education and social training in the field; diverse economic factors; lack of regulatory framework and infrastructure for biogas/biomethane; and public policy deficiencies.

Concerning public policy, this research phase analyzed the existing policies for Brazil and Mexico related to biogas and biomethane to evaluate their strengths and weaknesses, targeting to detect the opportunities to recommend possible improvements. These regulations are the National Solid Waste Plan (PNRS, 2010), National Basic Sanitation Plan (PLANSAB, 2013), National Energy Plan 2050 (PNE, 2020), Ten-Year Energy Expansion Plan (PDE, 2020); RenovaBio Program (2017); among others of less impact on the Brazilian case. For Mexico: General law for the prevention and integral management of solid waste (2018); The general law on climate change (2018); Transition Strategy to Promote the Use of Cleaner Technologies and Fuels (2020); Intersecretary Strategy for Bioenergetics (2009); The Law for the Promotion and

Development of Bioenergetics (2008); Electric Industry Law (2014); among others. These regulations can further encourage and develop biogas projects to properly manage the OFMSW, bioenergy production, nutrient recycling, and GHG mitigation, among other benefits.

The crucial conclusions derived from this research phase analysis in the case of Brazil is that for the adequate treatment of the OFMSW through AD, the diverse stakeholders firstly must comply with the already existing regulations to avoid landfilling and foster the harnessing of materials or energy in the waste. Also, municipalities must implement more effective actions in the non-generation, reuse, and source segregation of MSW. For this to happen, the Federal and State governments shall support municipalities or consortia of municipalities for the adequate treatment of MSW. In Brazil, the advantages of biodigestion have been proven; thus, these cases shall be spread and shared with diverse stakeholders to disseminate further the benefits of these technologies to treat waste, produce bioenergy and recycle nutrients successfully. New educational policies shall also be encouraged to help raise consciousness for the adequate disposal of residues and include social participation to create demands for implementing these projects.

Additionally, government officials should pursue the economic viability of these projects with diverse strategies such as incentives or benefits to make projects profitable for the private sector. They also should incorporate legislative measures and restrictions to ensure the environmental sustainability of the projects. Furthermore, according to the new gas law, city administrators should also articulate and integrate the biogas markets, investing in expanding gas networks and services and incentivizing biomethane as an urban transportation fuel. Additionally, government officials should include new amendments to the current legislation to incentivize and encourage biogas technologies. The development and advancement of public policies and the performance of financing agencies to support the sector will play a significant role in the expansion of biogas.

In the case of Mexico, it can be concluded that there would not be advances in the implementation of biogas projects for OFMSW if landfills are still the solution considered as optimal by law for the treatment of wastes. Municipalities must develop more effective actions in the non-generation, reuse, and waste segregation of MSW. Educational programs shall be created to raise consciousness for the adequate disposal of residues, thus including more society participation and its relevant role. Garbage pickers shall be formally considered in the governance network so that they can be adequately treated and remunerated. Also, the financial conditions must be created, with new regulations or incentives, to reach these technologies' economic viability. With this, the sustainability of these projects must be ensured by establishing regulations to mitigate any environmental impacts and using biogas as an environmental service. It shall also be relevant to make biomethane compatible in the vehicle industry and create a biofuel market and the infrastructure to allow fair competition with other fuels. Bioenergy technologies must compete with each other and not against other renewable energies. Investment in talent training and research & development would allow the technological learning curve to advance faster. Thus, new regulations and policies shall develop more coercive measures to treat OFMSW and sewage sludge through biodigesters. Stakeholders shall also consider the recuperation of nutrients as a fundamental principle of the circular economy.

6 CONCLUSIONS

Firstly, this research allowed to determine that diverse Organic Waste to Energy (OWtE) techniques currently treat the OFMSW in LAC, mainly with biochemical and thermochemical principles. In recent years, diverse entities have implemented various small and large-scale OWtE projects, and several studies have presented environmental and technical analyses of different OWtE technologies in LAC. Throughout this literature review, we found out that OWtE technologies are not always the better option; the benefits of keeping agricultural residues on the fields or treating the wastes through composting techniques cannot be neglected.

The feasibility of implementing one technology over the other for each residue is not set in stone but rather depends on each country's conditions and mainly on market and technological factors. Therefore, there is a need for genuine analyses and studies for each unique case. Nevertheless, the review of these technologies' state of the art resulted in anaerobic digestion and gasification being deemed the two most promising technologies, given the technical and environmental advantages they offer. Both technologies contribute to improving waste and energy systems along with several social and economic benefits; and can be complementary since they are optimal to treat different types of residues (more humid for DA and more lignocellulosic for gasification).

The second research phase results demonstrate that the dry anaerobic digestion system utilizes less water through its processes, as one of its main advantages. At the same time, the water needs of WAD systems do not represent large amounts, and the resulted liquids can be utilized to fertirigate crops or plantations. The biosolids quality must comply with the Resolution N° 498, emitted in 2020 by the Environmental National Council (CONAMA).

Another detected advantage of the DAD system is that it produces almost 2.5 more solid digestate or biofertilizer, with roughly 233 kg/tonne OFMSW compared to the 100 kg/tonne OFMSW of the WAD plant. It also tolerates impurities content, resulting in a more robust system.

As for the energy performance, the results disclose the energy efficiency of the AD2 system, even though it produces less biogas than AD1 (290.91 m^3 per tonne OFMSW for the AD1 compared to just 55 m^3/tonne OFMSW of the AD2). The disadvantage of AD1 comes when the energy consumption by the plant is considered. In this plant, a total of 700 kWh is supplied every day (1,273 kWh/tonne OFMSW) to maintain the plant running; the AD2 utilizes 374 kWh/day. The energy efficiency is represented by the energy ratio (ER), which shows that currently for the AD2, 26.4% of the energy contained in the biogas produced is utilized for the internal usage of the plant. Whereas for AD1, the energy consumed represents approximately 68% of the total energy produced. This is attributed to the fact that even when AD1 is much smaller it demands large amounts of energy for its pumps and mixing systems operations.

As future scenarios for the Option 1 of biomethane production for AD2; the plant could reach an estimated production of 345.5 kWh/tonne OFMSW resulting in an ER of 6.4%. However, if biomethane is produced in this plant there would be an extra consumption of energy, which is unknown and not considered in this study. In the case of AD1, the plant already consumes around 68% of the total energy contained in the biomethane produced.

The Option 2 of electricity and thermal energy production in the CHP unit also shows the efficiency of AD2 considering that in the case that the plant utilizes also its thermal energy produced; the consumption of energy within the plant would represent only around 4.8% of the total energy production. On the other hand, in the case a CHP unit (with similar characteristics) was implemented in AD1, still the plant would consume 63% of all the energy it would produce.

Regarding GHG mitigation potential, results demonstrate also the potential of wet systems, considering their significant biogas production rates. For the Option 1 of biomethane production, AD1 can save up to 3,573.8 kg CO_{2eq}/tonne OFMSW, while AD2 around 697.7 kg CO_{2eq}/tonne OFMSW; this is 5.1 times more. However, when it comes to the plant's direct emissions due to its electricity consumption and CH_4 leakages per treated tonne of OFMSW, AD2 emits far fewer GHG´s. With 14 kg CO_{2eq}/tonne OFMSW for AD2 and 201 kg CO_{2eq}/tonne OFMSW for AD1, the DAD system emits only around 7% (or 14.3 times less) of the total emitted by the WAD system. Furthermore, the CO_{2eq} savings ratio demonstrated that for AD1, 6% of the total CO_{2eq} saved are emitted via electricity consumption and CH_4 losses. For the AD2, only 2% of the total CO_{2eq} potentially saved is emitted. These results also show the effectiveness of both systems, although results show that the DAD plant can save more emissions than what it emits.

For the Option 2 of electricity and heat generation, results show for the AD2 the GHG emitted would be approximately 33% of the total emissions potentially saved. In the case of AD1, considering a suggested CHP production unit of 200 kWh of electricity and 363.64 kWh of heat per day, results show that the plant would emit more GHG´s (205.86 kg CO_{2eq}/tonne OFMSW) than what it can actually save (186.75 kg CO_{2eq}/tonne OFMSW) resulting in an ER of 110%. This is attributed to its high energy consumption and supposed methane leakages and losses of 1%.

Thus, these results help conclude that even when the WAD system offers advantages of water and resource savings, energy generation, and large CO_{2eq} savings, there is a notable significant higher efficiency on the DAD system. It utilizes less water through its processes; it produces almost 2.5 more solid digestate or biofertilizer; it has significant energy efficiency, using internally less energy of the biogas produced. It also presents a more significant GHG mitigation potential. Furthermore, the fact that it is a simpler technology allows for other advantages and benefits to the DAD system, such as robustness, less maintenance and technical complexity.

Lastly, the study third phase resulted in the proposal of the policy guidelines and recommendations for implementing AD and DAD technologies in Brazil and Mexico. Finding out that in Brazil and Mexico, there is to date a coherent legal framework, with several laws, strategies, and programs that mention, encourage, and promote the implementation of biodigesters for the adequate treatment and energy use of the OFMSW. However, these mandates and regulations are still general and little heeded. This waste fraction is mainly buried, burned, or sent to landfills without developing its energy and material potential (e.g., biofertilizers).

Thus, to develop the potential for adequate treatment of OFMSW through AD in both countries, it is considered that the States should determinately encourage and create the enabling conditions to address the issue. For this purpose, this study resulted in a series of policy guidelines and recommendations that may serve to develop a national political plan. These are orientated to prepare and implement new legislation and reforms to build more specific and coercive measures for the adequate treatment of OFMSW with biodigesters. These policy actions could be organized and presented in a State Plan for the Integral Management of the OFMSW. They shall be practical, cost-effective, and socially acceptable.

Currently, both countries present some challenges that hinder the implementation of such projects at a constant rate. In general terms, some of these challenges are given, according to this research findings, due to landfill and dumpsites overuse; lack of waste segregation systems; lack of knowledge or interest in AD technologies; low education and social training in the field; diverse economic factors; lack of regulatory framework and infrastructure for biogas/biomethane; and public policy deficiencies.

The crucial conclusions derived from this research phase analysis in the case of Brazil is that for the adequate treatment of the OFMSW through AD, the diverse stakeholders firstly must comply with the already existing regulations to avoid landfilling and foster the harnessing of materials or energy in the waste. Municipalities must implement more effective actions in the non-generation, reuse, and source segregation of MSW; for this to happen, the Federal and State governments shall support municipalities or consortia of municipalities for the adequate treatment of MSW. In Brazil, the advantages of biodigestion have been proven; thus, these cases shall be spread and shared with diverse stakeholders to disseminate further the benefits of these technologies to treat waste, produce bioenergy and recycle nutrients successfully. New educational policies shall also be encouraged to help raise consciousness for the adequate disposal of residues and include social participation to create demands for implementing these projects.

At the same time, government officials should pursue the economic viability of these projects with diverse strategies such as incentives or benefits to make projects profitable for the private sector. They also should incorporate legislative measures and restrictions to ensure the environmental sustainability of the projects. Furthermore, according to the new gas law, city administrators shall also articulate and integrate the biogas markets, investing in expanding gas networks and services and incentivizing biomethane as an urban transportation fuel. Additionally, new amendments and inclusions to the current legislation should be proposed to incentivize and encourage these technologies. The development and advancement of public policies and the performance of financing agencies to support the sector will play a significant role in the expansion of biogas.

In the case of Mexico, it can be concluded that there would not be advances in the implementation of biogas projects for OFMSW if landfills are still the solution considered as optimal by law for the treatment of wastes. Municipalities must develop more effective actions in the non-generation, reuse, and waste segregation of MSW. Educational programs shall be created to raise consciousness for the adequate disposal of residues, thus including more society participation and its relevant role. Garbage pickers (in Spanish pepenadores) shall be formally considered in the governance network to be adequately treated and remunerated. Also, the financial conditions must be created with new regulations or incentives to reaching this technology's economic viability. With this, the sustainability of these projects must be ensured by establishing regulations to mitigate any environmental impacts and using biogas as an environmental service. It shall also be relevant to make biomethane compatible in the vehicle industry and create a biofuel market and the infrastructure to allow fair competition with other fuels. Bioenergy technologies must compete with each other and not against other renewable energies. Investment in talent training and research & development would allow the technological learning curve to advance faster. Thus, new biomethane-specific regulations and policies are needed to adequately develop more coercive measures to treat OFMSW and sewage sludge through biodigesters. Stakeholders shall also consider the recuperation of nutrients as a fundamental principle of the circular economy.

The benefits obtained by biodigesters for the adequate treatment of OFMSW are diverse and already widely publicized; however, there are still several technical, financial, and political challenges. More specific actions are required for their successful implementation. It is also essential to account that change in waste management practices does not come in a short period but is a lengthy process where social participation and political will need to be built up over long periods. It demands the commitment of government officials and stakeholders for various years considering the shifts of political administrations.

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ANNEXES

See the following Appendices annexed

A. Case study protocol
B. Life Cycle Inventory (LCI)_CIBiogas
C. Life Cycle Inventory (LCI)_UFMG
D. Questionnaire to researchers and specialists in Brazil and México
E. Questionnaire to public policy specialist in Brazil
F. Questionnaire to public policy specialist in Mexico
G. General information and characteristics of WAD treatment plant_CIBiogas
H. General information and characteristics of DAD treatment plant_Caju
I. Overall GHG emissions and mitigation of WAD and DAD treatment plant

Annex A. Case study protocol

1. Preamble and General information

The objective of this project´s phase is to determine the technical and environmental benefits and/or disadvantages of DAD technologies in Brazil and Mexico through case study analysis. This project carries out two case studies of existing DAD plants: and compare them with the resource and environmental performance of two WAD also already constructed in Brazil and Mexico.

The case studies aim to analyze though Mass Flow Analysis (MFA) the effects of DAD in waste management, energy generation and water savings, in comparison with WAD systems, with a quantitative research approach. Complementarily, the study carries out an analysis to determine the GHG emissions of both systems types and find out how much DAD and WAD can help to meet NDC´s goals.

Primary numerical data will be obtained through interviews and questionnaires; and secondary from archives, reports and documents. Hereafter a detailed description of the procedure and research characteristics to follow for each of the four study cases, which shall be applied uniformly. Hence, the purpose of this protocol is to describe the research steps to carry out each study case in uniformity, as well as the general descriptions of the research tools and methods utilized.

2. Procedures

These procedures will be used uniformly for all the cases to avoid any discrepancies on the results, and contribute to rigour the methods and validity of the results.

1. General scheme of the Mass Flow Analyses (MFA) and Life Cycle Inventory (LCI): In order to refine the search of specific information, the LCI and MFA schemes will be previously developed. This shall help to obtain the precise information needed for the analyses. See Chapter 3.2.3.1. of the Objectives and Methodology document; and 3.4 of this document.
2. Initial contact with potential participants: With a formal letter invite, researchers and specialists to collaborate to the project (develop a template letter). Contact via email and/or telephone, describing in detail the purpose of the project. Schedule site visits and request, if possible, the photography documentation of the project. See Annex 1 for template letter.
3. Interviews and questionnaires: Carry out the interviews and questionnaires to the specialists of each organization. The detailed strategy to develop on this is in Chapter 3.3.
4. Archival research: Request documents, reports, information, etc. to the specialists. Obtaining data from various sources will allow for triangulation, which will help to increase the validity of the research. See Chapter 3.2.2.1.2 (of the Objectives and Methodology document) for detailed description.
5. Develop the Life Cycle Inventory: Once the data and all information possible was obtained, an inventory will be developed for each of the systems, where all materials, energy and water flows shall be stated, including general specifications. See Chapter 3.4.
6. Develop the Mass Flow Analysis: Develop the mass flow system for each case study and calculate the material, energy and water balances, and CO_2 equivalent emissions.
7. Develop the stocks & flows Diagram: This diagram helps to represent graphically the material, waste and energy flows. Where the energy flows are presented with line widths.

8. Analysis: Through specific detailed analyses, determine the potential benefits or impacts for each category. The detailed description of the analysis process is in Chapter 3.2.3.

3. Research Tools

3.1 Documents and archives:

Collection of secondary data to determine quantities and percentages of materials inputs and outputs, GHG emissions and thus find out how much DAD technologies can benefit water management, waste savings, and energy systems, and their NDC´s contributions. Through archival research method: Technical reports, publications, meeting minutes and previously collected measurements.

3.2 STAN Software:

The Software STAN v2.5 serves in this project to conduct the MFA analyses. This Software also helps to graphically display the MFA results. Further description in Chapter 3.2.3.1. of the Objectives and Methodology document.

3.3 Interviews and questionnaires:

The study carries out interviews and questionnaires to obtain primary data related to the quality of the treatment processes. Based on specific questions to the specialists or researchers in the studied anaerobic digestion plants, related to performance in the waste treatment, water use, energy generation, and GHG emissions.

Being that the numerical data shall be obtained in the reports, archives collected, and tabulations; the intention of the questionnaires are rather focused to obtain information related to the quality of the processes. Also to obtain as much information as possible of the AD treatments. The questions are:

Related to the material inputs:

- What are the material treated in the AD plant?
- How the materials are brought to the treatment sites? Which transportation system, and how far?
- What is their composition of total solids? is there consistency in these contents?
- What is the purity of the material arrived into the treatment plan? if not pure,
- What are the other components of the materials?
- What is the material input capacity?

In relation to the treatment processes:

- What is the holding retention time?
- Have there been any disturbances during the processes? If so, what are these?
- Are the processes being monitored?

Social aspects:

- *How is the social acceptance of the project?*
- *Is there any shareholder opposing the development of the project?*

- *Do the people living in the area agree or disagree with the project?*
- *How many jobs does the project creates?*

About the outputs and emissions:

- What is the quality of the resulted digestate? Is it commercialized or anyhow utilized?
- What is the use of the biogas produced in the plant? what is the frequency of biogas production?
- What gasses are emitted and how frequently?
- Is there any leachate produced throughout the treatment processes?

Others:

- Is there any pretreatment carried out?
- Which inoculum is used? Where is it brought from?
- What is the environmental performance of the plant?

Documents shall help to sustain this information and at the same time create triangulation to also increase the validity of the research. The order of the questions may attempt to follow the systems flow and any open to include any other question that may arise. General description of the strategy is in Chapter 3.2.2.1.1. of the Objectives and Methodology document.

Annex B. Life Cycle Inventory (LCI)_CIBiogas

Questionnaire & Life Cycle Inventory to CIBiogas wet treatment plant

Date: 02.04.21

Interviewer

Project Title	Dry anaerobic digestion potential for municipal organic waste treatment in Brazil and Mexico.
Institute	Institute of Energy and Environment (IEE)/ Grupo de Pesquisa em Bioenergia (GBio)
University	São Paulo University (USP)
Contact name	Rodolfo Daniel Silva Martínez
Email	rodolfo.silva.m@usp.br

Interviewed

Project name	Usina de Biogás da Itaipu em Foz de Iguaçu (Unidade de Demonstração – UD ITAIPU)
Location	Foz do Iguaçu
Institute	CIBiogas
Contact name	Larissa Schmoeller Brandt Breno Pinheiro Bruna Smaniotto Tiago Joelzer Marteres
Email	larissa.s@cibiogas.org breno.pinheiro@cibiogas.org bruna.smaniotto@cibiogas.org tiago@cibiogas.org

Note: The purpose of the following questionnaire and life cycle inventory is to collect all possible data from researchers and/or managers of existing large-scale anaerobic digesters that treat the organic fraction of municipal solid waste (OFMSW) in Mexico and Brazil. Thus helping to determine their advantages and disadvantages in comparison with similar technologies.

Questionnaire

The intention of this questionnaire is to obtain primary data related to the quality of the OFMSW treatment processes. Based on specific questions about the performance of the waste treatment, water use, energy generation, and GHG emissions. In addition, questions seek to obtain as much information as possible of the AD treatments. The order of the questions may attempt to follow the systems flow.

1. *Related to the substrate inputs:*

1.1. What are the substrates treated in the AD plant?

A UD ITAIPU utiliza, prioritariamente, os resíduos orgânicos dos restaurantes da área da Itaipu Binacional como substratos para produção de biogás, embora, eventualmente, processe resíduos externos oriundas apreensões da Polícia Federal, Polícia Rodoviária Federal, Receita Federal e Ministério da Agricultura, Pecuária e Abastecimento (MAPA). Esses resíduos externos são criteriosamente avaliados e fiscalizados pelos órgãos governamentais e contribuem para o incremento da produção de biogás e biometano. Importante frisar que sempre são realizados testes laboratoriais em amostra do substrato externo a ser recebido (caso este ainda não esteja cadastrado no banco de dados do laboratório). Os substratos externos mais comuns são: óleo de soja/milho, feijão, achocolatado em pó (cacau), milho, peixes, camarão, embutidos, frutas, cerveja, queijos, alhos, entre outros.

OBS: importante lembrar que esses resíduos provenientes de apreensões da Receita Federal e MAPA, milho, soja, feijão no geral os grãos já chegam a unidade para tratamento em processo de degradação, muito diferente de suas formas reais após colheita desses grãos.

1.2. How are they transferred to the treatment sites? What is the distance of transference?

Os resíduos orgânicos são armazenados diariamente em sacos plásticos, em seguida é realizada as retiradas dos resíduos por transporte com caminhões da terceirizada da Itaipu. A distância dos restaurantes até a planta é em torno de 2 km. Os processos existentes na unidade não utilizam nenhum combustível fóssil.

1.3. What is their composition of total solids?

Em média 12 %, esse teor de sólidos é muito relativo, temos variações de 5 a 15% a cada entrega de RSO, no após o processo de triagem dos resíduos temos triturador que é lubrificado com H_2O que altera a sua composição do RSO, e não era feito o controle dessa adição de H_2O.

1.4. What is the purity of substrates arriving at the treatment plant? Are they contaminated?

É necessário remover materiais não orgânicos, como plásticos ou talheres de metal, que é realizada pelos operadores da planta, mas no geral, os resíduos estão razoavelmente bem separados ao chegar na planta.

1.5. If so, what are the other components?

Plásticos (copos descartáveis), latas de alumínio (sucos, refrigerantes) e talheres de metal.

2. *In relation to the treatment processes:*

2.1. How long do the treatment processes take before biodigestion?

Para a quantidade atual de resíduos recebidos, leva em torno de 2 horas.

2.2. Have there been any disturbances during the processes? If so, what were them?

Não há distúrbios.

2.3. Are the processes being monitored?

Os processos monitorados atualmente são:

- Temperatura da biomassa (sensores de temperatura em 3 pontos nos biorreatores);
- Nível de biomassa nos reatores (sensor de nível ultrassônico);

- pH da biomassa (sensor de pH);
- A carga orgânica volumétrica é mantida constante.
- Além disso, alguns parâmetros físico-químicos também são monitorados: pH, FOS/TAC, amônio (mg/L NH4+), sólidos totais, sólidos fixos e sólidos voláteis (g/kg), além do potencial bioquímico de metano (BPM), no caso de novos substratos.

3. *About the outputs and emissions:*

3.1. What is the quality of the resulted digestate? Is it () commercialized or () somehow utilized in-situ or () donated or (X) or disposed?

3.2. What is the use of the biogas produced in the plant?

O biogás passa por processos de refino para ser utilizado como combustível no abastecimento da frota de veículos movidos a biometano da Itaipu.

3.3. Is the biogas treated and converted into biomethane?

Sim, como explicado acima, com remoção de H2S por carvão ativado, remoção de CO_2 por Sistema de "water scrubbing" e remoção de umidade por PSA.

Qual é a quantidade de biometano conteúda no biogás produzido? 58,5% de CH4

3.4. What gasses are leaked or emitted and how frequently?

Ocorre a emissão de CO_2 durante o processo de refino, além de uma parcela de CH4 que é perdida durante o processo de remoção do CO_2.

3.5. What oils or other resources are emitted throughout the processes?

Não ocorre emissão de óleos ou outros resíduos.

3.6. Is there any leachate produced throughout the treatment processes? If so, what is its composition and how much is it produced? How is it treated or discarded?

Não há produção de lixiviado durante os processos da planta.

4. *Social aspects:*

4.1. What is the social acceptance of the project? Do the people living in the area agree or disagree with the project?

A planta está instalada dentro do complexo Itaipu, em frente ao mirante do vertedouro da usina, não causando impacto social em relação a população.
A unidade recebe visitas técnicas com frequência, de escolas, universidades, empresas diversas e também de eventos diversos.

4.2. Is there any shareholder opposing the development of the project?

Não.

4.3. How many job positions does the project creates? How many are women?

- Operação terceirizada – 3 operadores que realizam as atividades de pre-tratamento (trituração dos alimentos) e manutenções gerais e limpeza da planta, sendo 2 homens e 1 mulher;
- Técnicos de operação e manutenção – 2 técnicos (homens);
- Gerência – 1 gerente (mulher);
- Fiscal do projeto – 2 fiscais do projeto (homens).

4.4. What other social benefits does this project bring to the communities?

- Realização de visitas técnicas;
- Compartilhamento de informações que podem ser usadas em projetos de maiores ou menores escalas, inclusive doméstica;
- Redução da quantidade de resíduos que são transportados ao aterro sanitário, aumentando a vida útil deste e aproveitando o potencial energético dos resíduos para a produção de combustíveis pelos poluentes, além de reduzir emissão de CH4 que ocorreria caso os resíduos fossem para o aterro;
- Redução da emissão de gases de efeito estufa com a substituição de combustíveis fósseis;

5. *Others:*

5.1. Is there any pretreatment carried out? What kind?

Apenas trituração dos resíduos dos restaurantes.

5.2. Which inoculum is used? Where is it taken from?

Para a inoculação e inicialização dos reatores foi utilizado dejetos bovinos de propriedades rurais da região.

5.3. What elements could be improved throughout the treatment process?

Implementação de medidores de vazão de biogás, pois hoje utilizamos cálculos teóricos para quantificação da produção do biogás. Além de medidores de vazão de entrada e saída de biomassa, para obtenção de valores mais precisos em relação ao tempo de retenção hidráulica, por exemplo, que atualmente também é estimado.

Am I missing any important information in your opinion?

Acredito que não.

Life Cycle Inventory

An inventory of the flows, stocks and treatment processes intends to have complete knowledge and understanding of the analyzed systems. Hence, the following Life Cycle Inventory (LCI) helps to create a detailed list of inputs, outputs and flows in the system in a daily basis. The purpose is to obtain any numerical and qualitative data for the study purposes including inputs of raw materials, energy and water releases to air, land and water. A general information section is also included to consider other possible aspects of the treatment plant.

1.	Substrates & water	Amount	Unit	4.	General Information	Facts
	Inputs				Enclosed	Sim
	Municipal Solid Waste	N/A			Type of fermenters	CSTR
	Organic Waste Fraction (Nota1)	800	Kg/day		Process steps	Nota 4
	Waste water *esgoto	0			Digestate separation	Peneira estática
	Potable water	0			Digestate storage	Lagoa
					Post composting	N/A
	Outputs				Dry matter content	12%

	Digestate (dry)	Nota 2	
	Digestate (dry) after composting (in case)	N/A	
	Liquid leachate	N/A	
	Digestate (water)	Nota 2	1 m^3/day
	Digestate (wet) after composting	N/A	
	Initial High calorific fraction (HCF)		
	High calorific fraction dry (HCFd)		
2.	**Energy Information**	**Amount**	**Unit**
	Inputs		
	Electricity consumption	Media 700	kWh/day
	Fuel (Diesel) consumption	N/A	
	Heat used internally	N/A	
	Outputs		
	Biogas produced	160	m^3/day
	Electricity produced **(Nota 7)**	200	kWh/day
	Heat produced	N/A	
	Electricity produced available	*N/A*	
	Heat produced available	*N/A*	
3.	**Green House Gasses**	**Amount**	**Unit**
	Calculated emissions (Nota 3)		
	Carbon dioxide (CO_2)		
	Fugitive methane (CH4)		
	Nitrous oxide (N2O)		
	Hydrogen Sulfide (H2S)		
	Others:		

Excess Water consumption	Nota 5
Temperature range	35 a 37°C
Mobil Machines necessary	Nota 6
Mixing tank	Sim, existe.
Batch	N/A
Fermenter position	Horizontal
Temperature	35 a 37°C
Process steps	
Digestate separation	Peneira estática
Digestate storage	Lagoa
Project footprint (area)	3.000 m²
Recirculation of Liquid digestate	Sim, é realizado
Dry digestate	N/A
Type of composting (if existent)	N/A
Storage of the organic waste	N/A
Time of digestate material in reactor	80 dias
Loading rate	80 dias
Quantities of oils emitted	N/A
Quantities of other emissions	N/A
Others:	N/A

Nota 1 - Soma dos resíduos de restaurantes em média chega a 250 kg, utilizamos em média 200 kg de cacau, 100 L de óleo.
Nota 2 – Atualmente, todo o digestato é utilizado para recirculação, por isso não está sendo feita a separação. Efluentes após de serem aproveitados no processo de biodigestor, são transferidos para

outro reator para melhor tratamento em parâmetros de DQO, Amônio, e iniciamos o acampamento de NPK.

Nota 3 - Parâmetros de emissão de gases não são calculados nessa planta.

Nota 4 – É realizada recirculação hidráulica do digestato na frequência de 2x por semana.

Nota 5 – É utilizado agua durante o processo de trituração dos resíduos, porém não é medida a quantidade.

Nota 6 – é utilizada empilhadeira para o recebimento dos resíduos e posicionamento da caçamba de recebimento na plataforma de trituração.

Nota 7 – Há previsão para inclusão de um gerador a biogás para geração de energia elétrica em caráter demonstrativo, porém sem data para início. Com a produção atual, a capacidade de geração seria em torno de 200 kWh/dia (caso todo o biogás produzido no dia seja utilizado para geração de energia).

Outras perguntas

- Se poderia estimar a quantidade de água que o projeto utiliza durante o processo de biodigestão? Informação costa também no 1.3
    - Não há, atualmente, um medidor de vazão de água de entrada porque é muito pouco utilizada no processo de biodigestão. A homogeneização é realizada com a própria biomassa (recirculação), então água somente entra em casos muito específicos ou para algum efeito de manutenção corretiva ou preventiva.
- Ou o esgoto gerado no complexo ITAIPU e usado no processo de biodigestão? Se poderia estimar a quantidade que é usada (input)? E a quantidade gerada depois da peneira desaguadora usada para fertirrigação (output)?

Esgoto não é utilizado no processo da unidade.

- Biofertilizantes são produzidos? Quanto? Se não, quanto poderia produzir hipoteticamente?

É produzido aproximadamente 1 m^3 por dia e é utilizado para fertirrigação da área verde da Itaipu, por meio de um caminhão.

- Se poderia estimar a quantidade de diesel ou combustível que é usada pela maquinaria dentro da usina?

Os processos existentes na unidade não utilizam nenhum combustível fóssil.

- Tem planejado a instalação de uma unidade de cogeração de energia elétrica e térmica além da produção de biometano? Se sim, qual seria o potencial de produção de eletricidade e calor possível?

Há previsão para inclusão de um gerador a biogás para geração de energia elétrica em caráter demonstrativo, porém sem data para início. Com a produção atual, a capacidade de geração seria em torno de 200 kWh/dia (caso todo o biogás produzido no dia seja utilizado para geração de energia).

Para esses resultados compartilhado na tabela abaixo, foram utilizados os seis (06) últimos ensaios de ST, SF e SV de resíduos RSO após o processo de triagem e trituração.

ST (%)	SF (%)	SV (%)	Massa específica	Fração calorífica
9,36	6,23	93,76	N/A	N/A

Annex C. Life Cycle Inventory (LCI)_UFMG

Questionnaire & Life Cycle Inventory of Caju dry treatment plant

Date: 17.02.21

Interviewer

Project Title	Dry anaerobic digestion potential for municipal organic waste treatment in Brazil and Mexico.
Institute	Institute of Energy and Environment (IEE)/ Grupo de Pesquisa em Bioenergia (GBio)
University	São Paulo University (USP)
Contact name	Rodolfo Daniel Silva Martínez
Email	rodolfo.silva.m@usp.br

Interviewed

Project name	Extra-Dry Methanization System (TMethar)
Location	Caju, Rio de Janeiro
Institute	Escola de Engenharia - Universidade Federal de Minas Gerais
Contact name	Prof. Carlos Chernicharo Dr. Bernardo Ornelas Ferreira
Email	calemos@desa.ufmg.br ornelas.ambiental@gmail.com

Note: The purpose of the following questionnaire and life cycle inventory is to collect all possible data of existing large-scale anaerobic digesters that treat the organic fraction of municipal solid waste (OFMSW). Thus helping to determine their environmental and technical performance.

Questionnaire

The intention of this questionnaire is to obtain primary data related to the quality of the OFMSW treatment processes. Based on specific questions about the performance of the waste treatment, water use, energy generation, and GHG emissions. In addition, questions seek to obtain as much information as possible of the AD treatment. The order of the questions attempts to follow the systems flow.

1. *Related to the substrate inputs:*
   1.1. What are the **substrates** treated in the AD plant?

A UTR-Caju recebe mais de 2.000 toneladas de FORSU por dia, coletadas de residências e grandes geradores, como centros de abastecimento (ex.: CEASA), redes de supermercados, restaurantes e hotéis.

Ao longo das Fases I, II e III, os reatores MESB receberam cargas de FORSU que variaram entre 56,6 e 77,8 toneladas, tendo sido testadas diferentes condições de carga, representados pelas Figura 7.4 e Tabela 7.6 a seguir.

Se formam pilhas de 2,5 m de altura em cada reator MESB.

   1.2. How are they **transferred** to the treatment sites? What is the distance of transference?

Em vista dessa redução de massa, a redução de custo de transporte e aterro é uma das principais vantagens da biotecnologia de metanização MESB.

There is no diesel consumption accounted for this since the biogas plant is located in the site where the residues are deposited.

   1.3. What is their composition of **total solids**?

Conteúdo de ST de 215 kgST.t-1 FORSU e um potencial de biodegradação (SV/ST) de 0,88 – que resulta em um conteúdo orgânico de 190 kgSV.t-1FORSU.

Massa específica média (560 kg.m-3FORSU).

   1.4. What is the **purity of substrates** arriving into the treatment plant? Are they contaminated?
   1.5. If so, what are the **other components**? And the percentages?
2. *In relation to the treatment processes:*
   2.1. **How long** do the treatment processes take?

30 days.

   2.2. Have there been **any disturbances during the processes**? If so, what were them?
   2.3. Are the processes being **monitored**?

O processo de tratamento biológico concebido na TMethar é basicamente divido em 5 etapas integradas: (i) recepção e preparo do resíduo orgânico; (ii) metanização em estado sólido via batelada sequencial (MESB) com recirculação de lixiviado estabilizado via UPI; (iii) pós-tratamento do material digerido (MD); (iv) armazenamento, dessulfurização e aproveitamento energético do biogás via CHP (Figura 4.5).

3. *About the outputs and emissions:*
   3.1. What is the quality of the resulted **digestate**? Is it () commercialized or () somehow utilized in-situ or () donated () or disposed?

O MD removido do reator MESB era encaminhado para uma etapa de maturação, para sua estabilização final. No sistema TMethar esta etapa de pós-tratamento do MD pode ser promovida nos próprios reatores MESB (via compostagem com aeração controlada) ou no pátio externo de compostagem.

3.2. What is the **use of the biogas** produced in the plant?

Não foi possível medir a vazão de biogás nos reatores MESB. 285 Nm^3 CH4.t-1SV. Para estimativa de potencial de produção de biogás nos reatores MESB foi assumida uma eficiência de aproveitamento de 70% do BMP (200 Nm^3 CH4.t -1SV).

Sob estas condições, a energia total disponível (ED) no biogás produzido pela TMethar é de aproximadamente 200 kW (Equação 8.6), que podem ser convertidos em energia renovável e/ou biocombustível veicular (biometano).

3.3. Is the biogas treated and converted into **biomethane**?

Teor médio de 60 %CH4

3.4. What **gasses are leaked or emitted** and how frequently?
3.5. What **oils or other resources** are **emitted** throughout the processes?
3.6. Is there any **leachate produced** throughout the treatment processes? If so, what is its composition and how much is it produced? How is it treated or discarded?

Volume de lixiviado fresco (LF) contido na FORSU de grande gerador (FORSU-GG), cujo volume médio de geração foi igual a 0,18 m^3LF.t-1FORSU

Conforme ilustra Figura 5.9 do Capítulo 5 desta tese. Conforme descrito no item 5.2.1, o LF vertido no Pátio de Resíduos é coletado pelos dispositivos de drenagem e encaminhado para o Tratamento Preliminar (TP) e, posteriormente, para UPI.

4. *Social aspects:*
   4.1. What is the **social acceptance of the project**? Do the people living in the area agree or disagree with the project?
   4.2. Is there any **shareholder opposing the development** of the project?
   4.3. **How many job positions** does the project creates? How many are **women**?
   4.4. What **other social benefits** does this project bring to the communities?

Tratamento de FORSU equivalente populacional de cerca de 25 mil habitantes.

5. *Others:*
   5.1. Is there any **pretreatment** carried out? What kind?

Ao chegar na TMethar, a FORSU-GG era descarregada no pátio de recepção de resíduos orgânicos, com área total de 200 m^2 e muro para a contenção de resíduos com 3,0 m de altura. Neste pátio era realizada a caracterização gravimétrica da FORSU e seu preparo para a introdução nos reatores MESB.

O lixiviado drenado do pátio de recebimento era encaminhado para unidade de tratamento preliminar (TP), figura 5.1, cujo objetivo era a remoção de sólidos grosseiros e areias, evitando o aporte de material inerte no reator biológico utilizado para estabilização do lixiviado (UPI)

5.2. Which **inoculum** is used? Where is it taken from?

Anaerobic sewage sludge taken from a digester of a municipal WWTP with volatile solid content of 20 g VS/L was used as inoculum for the BMP tests.

5.3. What **elements could be improved** throughout the treatment process?
5.4. Am I missing any **important information** in your opinion?

Digestate: A produção de biosólido, um importante subproduto da metanização, foi estimada conforme Tabela 8.2, cujos valor de redução de massa adotado para o material digerido foi 40%, conforme estudos de Pognani et al., (2015) e Di Maria et al., (2017c), e uma eficiência de recuperação de 50% do material após a etapa de peneiramento com malha de 10 mm (Equação 8.4 e Equação 8.5).

Após a batelada MESB, o MD produzido é encaminhado para etapa de peneiramento, visando a remoção de materiais inertes e dos resíduos orgânicos com granulometria maior que 10 mm. Considerando uma eficiência de recuperação de 50% do MD como biosólido, espera-se uma produção de 109 tBiossólidos.mês-1 (Equação 8.5), o que equivale a uma produtividade de 233 kgBiossólido.t - 1RSU. Destaca-se ainda que, quanto maior a eficácia da etapa de segregação de resíduos (remoção de inertes) e menor a granulometria da FORSU (trituração), maior a produtividade de biosólido pelo sistema de metanização.

Pós-tratamento: Vale ressaltar ainda que, os processos de metanização demandam uma etapa de pós-tratamento para o polimento do efluente final (remoção de sólidos suspensos + estabilização da matéria orgânica remanescente), possibilitando seu lançamento e/ou seguro no meio ambiente (CHERNICHARO, 2007).

Annex D. Questionnaire to researchers and specialists in Brazil and México

Questionnaire

Following, some standardized questions to obtain information from your perspective as a researcher, specialist or decision maker considering the conditions in Brazil and México respectively.

Waste Management Generalities

1. Should traditional OSW´s treatment means, such as landfilling and dumpsites, keep being implemented? should new developments of these treatment methods be encouraged or banned? Why?
2. Could a waste source segregation system be implemented and thrive in the cities and towns? Would it represent an advantage for the treatment of OSW?
3. Are traditional wet and/or dry biodigesters a feasible technology to treat OSW in these countries?
4. Which specific AD technology (from Figure 1) is the most appropriate to treat OSW residues? Why?

DAD Technical

5. Why do dry anaerobic digestion (DAD) technologies haven´t been implemented and promoted? Please number in order of importance (Number 1 = main reason); and/or "Na" if it does not apply.

_ No financial viability/ high prices
_ Technical complexity
_ Lack of knowledge of the existence of these systems
_ Lack of interest of stakeholders. Which of them: _________________
_ Public policy deficiencies
_ No concern of environmental issues
_ Other(s): _________________

6. What are the challenges to implement DAD systems?

7. Would the less water utilization represent an advantage for DAD over WAD (wet anaerobic digestion) systems? (Mainly in dry or semidry regions).

8. Can DAD technologies significantly contribute to reach the countries' GHG reduction goals, according to the Nationally Determined Contributions (NDC´s) goals?

Economic

9. Could these technologies turn (or be more) financially viable in the future? what needs to be done?

10. Would the development of AD biodigesters with local materials and technologies, specific for the country conditions, contribute to the development of DAD projects? and is there the structural capacity and technical knowhow to develop such a technology in these countries?

Policy

11. Why previous public policies and regulations that have fostered the implementation of anaerobic digestion projects have not continued and prevailed?

12. What are the flaws of the current legislation related to AD systems? What is missing?

13. Are current policies significantly contributing to the implementation of AD projects?

14. Could you propose recommendations or strategy on how to foster the implementation and dissemination of AD technologies, and more specifically DAD projects;

15. Am I missing any important information in your opinion?

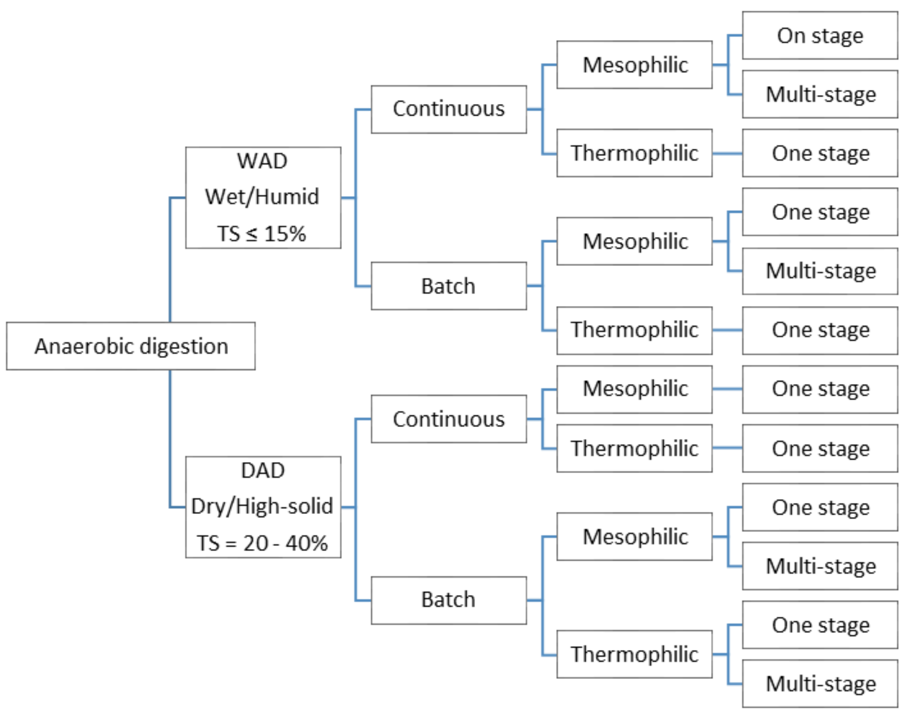

Figure 1: General classification of anaerobic digester types. Source: adapted from IBTech, 2020 [317]

Annex E. Questionnaire to public policy specialist in Brazil

Questionnaire

Following, some standardized questions to obtain information from your perspective as a researcher, specialist or decision maker considering the current conditions of biogas and biomethane from a Waste to Energy viewpoint in Brazil.

Current Policies

1. What is the intention of the Brazilian government to lead low carbon energy systems? How biogas contributing in this task? *Qual é a intenção do governo brasileiro de liderar sistemas de energia de baixo carbono? Como o biogás está contribuindo nessa tarefa?*

2. Could the RenovaBio program be improved to incentivize more the implementation of biogas projects? If yes, could you elaborate on how? If no, why?
   O programa RenovaBio poderia ser aprimorado para incentivar mais a implementação de projetos de biogás? Se sim, você poderia explicar como? Se não, por quê?

3. Could the PNRS (Plano nacional de resíduos sólidos) be reformed and improved to incentivize biogas projects? If yes, could you elaborate on how? If no, why?
   O PNRS poderia ser reformado e aprimorado para incentivar projetos de biogás? Se sim, você poderia explicar como? Se não, por quê?

4. Do you think that the PDE (Plano decenal de energia) should include a larger portion of biogas in the energy matrix by 2029? If yes, by how much and why? If no, why?
   Você acha que o PDE deve incluir uma porção maior de biogás na matriz energética até 2029? Se sim, por quanto e por quê? Se não, por quê?

5. Which other political instruments are necessary to overcome the challenges to expand biogas in the national energy matrix? *Quais outros instrumentos políticos são necessários para superar os desafios da expansão do biogás na matriz energética nacional?*

6. Do you think a specific new law; program or regulation should be developed to incentivize the implementation of biogas projects for the treatment of OSW?
   Você acredita que alguma nova lei, programa ou regulamento específico devem ser desenvolvidos para incentivar a implementação de projetos de biogás para o tratamento da fração orgânica dos Resíduos Sólidos Orgânicos (RSO)?

Dry Anaerobic Digestion

7. Which specific AD technology (from Figure 1) is the most appropriate to treat OSW residues in the country? Why?
   Qual tecnologia específica de DA (Fig. 1) é a mais apropriada para tratar RSO no país?; por quê?

8. What are the challenges to implement DAD systems? *Quais são os desafios para implementar os sistemas DAD?*

9. Could these technologies turn financially viable in the future? What needs to be done?
   Essas tecnologias poderiam se tornar (ou ser mais) financeiramente viáveis no futuro?; O que precisa ser feito?

10. Would the development of a particular national DAD technology, specific for the country conditions, contribute to the development of more projects? and is there the structural capacity and technical knowhow to develop such a technology in Brazil?
    O desenvolvimento de uma tecnologia nacional particular de DA, específica para as condições do país, contribuiria para o desenvolvimento de mais projetos?; e existe a capacidade estrutural e o conhecimento técnico para desenvolver essa tecnologia no Brasil?

Social contributions

11. What is the importance of the society participation for the implementation of biogas WtE projects? and would the implementation of these technologies contribute to social development?
    Qual a importância da participação da sociedade para a implementação de projetos de "Waste to Energy" de biogás? E essas tecnologias ser um agente para o desenvolvimento social?

Environment and sustainable use of natural resources

12. What could be done or included in the current legislation to mitigate the possible environmental degradation (e.g. arable land occupation, forest degradation, etc.) caused by biogas (1st generation) and other biofuels developments?
    O que poderia ser feito ou incluído na legislação atual para mitigar a possível degradação ambiental (por exemplo, ocupação de terras aráveis, degradação de florestas, etc.) causada pelo desenvolvimento de biogás (1ª geração) e outros biocombustíveis?

Energy Markets

13. What are the opportunities and barriers that can be created for the biogas sector by the new gas market in Brazil?
    Quais são as oportunidades e barreiras que podem ser criadas para o setor de biogás pelo novo mercado de gás no Brasil?

14. Do you think biomethane should be more incentivized than gasoline, diesel and ethanol as a transportation urban fuel and for heavy load trucks? Why?
    Você acredita que o biometano deveria ser mais incentivado do que a gasolina, o diesel e o etanol como combustível de transporte urbano e transporte de carga pesada? Por quê?

15. Would you have any other recommendation to foster biogas projects for the treatment of OSW?
    Você tem alguma outra recomendação para promover tecnologias de DA para o tratamento dos RSO?

Annex F. Questionnaire to public policy specialist in Mexico

Questionnaire

Following, some standardized questions to obtain information from your perspective as a researcher, specialist and/or decision maker considering the current conditions of biogas and biomethane from a Waste to Energy viewpoint in Mexico.

Current Policies

1. Why the initiatives and attempts since 2005 to install biogas projects (e.g. Firco / Sagarpa financing) have not achieved the expected results on more and efficient biodigesters implementation?
   Por qué las iniciativas y tentativas desde el 2005 para instalar proyectos de biogás (por ejemplo, financiamientos Firco/Sagarpa) no han alcanzado los resultados esperados y la eficiente implementación de biodigestores?

2. How relevant would it be to establish the requirement of Clean Thermal Energy Certificates (CETEL) - as it already exists with Clean Energy Certificates (CEL) for electricity - to encourage greater participation of biogas in the national energy matrix? Why?
   ¿Qué tan relevante sería el establecer la exigencia de los Certificados de energía térmica limpia (CETEL) - cómo ya existe con los certificados de energía limpia (CEL) para electricidad - para incentivar mayor participación del biogás en la matriz energética nacional? ¿Por qué?

3. Renewable promotion programs such as PRONASE, and PROINBIOS (among others), already promote the participation of renewables, however, bioenergy and biogas have lagged behind in the last places of clean energy in the country (Gutiérrez, 2018); how to increase biogas participation in these (or other) programs?
   Los programas de fomento a renovables como el PRONASE, y el PROINBIOS (entre otros), ya fomentan la participación de renovables, sin embargo, la bioenergía y el biogás han quedado rezagados a los últimos lugares de energía limpia en el país (Gutiérrez, 2018); cómo hacer para incrementar la participación del biogás en estos (u otros) programas?

4. Could something be added or reformed to the "Law for the Promotion and Development of Bioenergetics", "Energy transition law" or "general law on climate change" to further incentivize biogas projects? What would these changes be?
   ¿Podría agregarse o reformarse algo a la "Ley de promoción y desarrollo de los Bioenergéticos" "Ley de transición energética" o "Ley General de Cambio Climático" para incentivar más los proyectos de biogás? ¿cuáles serían estos cambios?

5. Could something be added or reformed to the "General Law for the Prevention and Integral Management of Solid Waste" to further incentivize biogas projects? What would these changes be? *¿Podría agregarse o reformarse algo a la "Ley General para la Prevención y Gestión Integral de los* Residuos Sólidos" para incentivar más los proyectos de biogás? ¿Cuáles serían estos cambios?

6. Do you consider that National Strategies such as the "Transition Strategy to Promote the Use of Cleaner Technologies and Fuels, 2019", or the "Intersecretary Strategy for Bioenergetics, 2009" consider biogas sufficiently to contribute to meet clean energy goals and the energy efficiency goal?
   ¿Considera que las Estrategias Nacionales tales como la "Estrategia de Transición para Promover el Uso de Tecnologías y Combustibles más Limpios, 2019", o la "Estrategia Intersecretarial de los Bioenergéticos, 2009" consideren los suficiente al biogás para contribuir a cumplir las metas de energías limpias y la meta de eficiencia energética?

7. What would you suggest to be a more effective and favorable policy (new law, strategy, or program) to promote the treatment of the OSW and other organic residues through anaerobic digestion?
   ¿Cuál sería una política más eficaz y favorable (nueva ley, estrategia, o programa) para promover el tratamiento de la FORSU y otros residuos orgánicos mediante digestión anaerobia?

Social contributions

8. What is the importance of the society participation for the implementation of biogas WtE projects? and would the implementation of these technologies contribute to social development?
   ¿Cuál es la importancia de la participación de la sociedad para la implementación de proyectos de biogás WtE? ¿Y contribuiría la implementación de estas tecnologías al desarrollo social?

Environment and sustainable use of natural resources

9. What could be done or included in the current legislation to mitigate the possible environmental degradation (e.g. arable land occupation, forest degradation, etc.) caused by biogas (1^{st} generation) and other biofuels developments?
   ¿Qué podría reformarse o incluirse en el marco legal actual para mitigar la posible degradación ambiental (por ejemplo, ocupación de tierras cultivables, degradación forestal, etc.) causada por el biogás (1ra generación) y otros desarrollos de biocombustibles?

Energy Markets

10. Could new financial incentives be created to foster the creation of biogas projects? Which could be an example? *¿podrían ser creados nuevos incentivos financieros para promover proyectos de biogás? ¿Cuáles podrían ser?*

11. Do you think biomethane should be more incentivized than gasoline, diesel and ethanol as a transportation urban fuel and for heavy load trucks? Why?
    ¿Usted considera que el biometano debería ser más incentivado que la gasolina, el diésel y el etanol como combustible para el transporte urbano y carga pesada? ¿Por qué?

12. Would you have any other recommendation to foster biogas projects for the treatment of OSW?
    ¿Tiene alguna otra recomendación para promover el tratamiento de los residuos orgánicos mediante tecnologías de digestión anaerobia?

Annex G. General information and characteristics of WAD treatment plant_CIBiogas

	1st- Wet biogas treatment					
	CIBiogás					
Inputs and Outputs	**Amount**	**Unit**	**Amount**	**Unit**		
Input material						
MSW (total)	NA					
OFMSW (FORSU + outros residuos)	0.55	ton FORSU/day	***550.00***	Kg/day		
Water or sewage water	0.00		0.00			
Water for other purposes	0.05	ton FORSU/day	50.00	Lit/dia		
Total OFMSW treated	0.60	ton FORSU/day	600.00	Kg/day		
Outputs material						
Digestate water recicled to bioreactor	0.00	Lit/ton FORSU	0.00	Ton/day		
Water Effluents discarded	0.00					
Biogas (15.9% check citation)	*159.00*	kg/ton FORSU	0.095	ton/day	15.90%	84.10%
Digestate solid/liquid (biofertilizer)	*841.00*	kg/ton FORSU	0.505	ton/day		
Solids in the digestate (Ts= 12%)	100.92	kg/ton FORSU	0.061	ton/day		
Liquid Water in the digestate (88%)	740.08	kg/ton FORSU	0.444	ton/day		
Remaining solid rejects	0.00					
	1,000.00		0.60			
Energy Information						
Electrical consumption	*1,272.73*	kWh/ton FORSU	***700.00***	kWh/day	255.50	MWh/a
Heat used internally	0.00		0.00		N/A	kWh/a
Electricity for Mechanical Treatment	NA				N/A	kWh/a
Diesel consumption	NA				N/A	l/a
Diesel fo Mechanical Treatment	NA				N/A	l/a
Energy used and produced						
Biogas produced	290.91	Nm^3/ton FORSU	***160.00***	m3/day	58,400.00	Nm^3/a
Electricity produced (generation capacity)	363.64	kWh/ton FORSU	200.00	kWh/day	73,000.00	kWh/a
Energy power (CHP installed capacity)	NA			KW		KWh/a
Heat produced (generation capacity)	0.00					
Biomethane (58.5%)	170.18	Nm^3/ton FORSU	93.60	m3/day	34,164.00	Nm^3/a
Methane leakages	2.91	Nm^3/ton FORSU	1.60	m3/day	584.00	Nm^3/a
General Information	**Facts**					
Enclosed	Yes					
Type of fermenters	CSTR					
Biological Process steps	1.00					
Digestate separation	Static sieve					
Digestate storage	Lagoon					
Post composting	No					
Mobil Machines neccesary	Yes					
Temperature range	35 a 37 °C	Mesophilic				
Caracteristicas dos resíduos						
Massa especifica media	NA					
Total Solids	12%					
Volatile Solids	94%					
Fixed Solids	6%					
High calorific value of Biogas	5.5	kWh/m3	*search citation			
High calorific value of Biomethane	11.06	kWh/m3				
Caracteristicas do Biogás						
Biogas CH4 content	58.5%					
Biogas CO2 content	38%					
Biogas H2S content	300 ppm					
Biogas O2 content	0.5%					
Fermentation specifications						
Storage of the input	Flat storage					
Mixingtank	Yes					
Fermenter position	Horizontal					
Recirculation of Liquid digestate	Yes					
Project footprint	3,000.00	m2				
Time of biodigestation process	80.00	days				
Quantities of oils used	N/A					
Quantities of other emissions	N/A					
Others	N/A					

Annex H. General information and characteristics of DAD treatment plant_Caju

	2nd case - Dry system							
	Cajú							
Inputs and Outputs	**Amount**	**Unit**	**Amount**	**Unit**				
Input material								
MSW (total)	4,000	Ton/dia			1,440,000.00	t/a	120,000.00	Ton/month
OFMSW (total)	2,000	ton FORSU/dia			720,000.00	t/a	60,000.00	Ton/month
OFMSW treated	***15.6***	ton FORSU/dia			5,616.00	t/a	468.00	Ton/month
OFMSW treated in the MESB(82%)	12.8	ton FORSU/dia						
Water or sewage water	0.0							
Water used for other purpuses	0				0.00			
Outputs material								
Biogas	79	kg/ton FORSU	1.23	Ton/dia				
Biogas biodigester	63	kg/ton FORSU	0.99	Ton/dia		1m3 biogas =	1.15	kg/m3
Biogas IPU	16	kg/ton FORSU	0.25	Ton/dia				
Sulphur & other solid pollutants (after CHP)	0.5	kg/ton FORSU	0.001	Ton/dia				
Digestate solid/liquid (biosolid) (60%)	***600***	kg/ton FORSU	9.36	Ton/dia	3,360.00	t/a	280.00	Ton/month
Biosolids (solid biofertilizer)	***233***	kg/ton FORSU	3.63	Ton/dia	1,308.00	t/a	109.00	Ton/month
Remaining rejects	***225***	kg/ton FORSU	3.51	Ton/dia				
Water still contained in the Digestate	142	Lit/ton FORSU	2.22	Ton/dia				
Fresh leachate (FL) After patio (18%)	180		2.81	Ton/dia				
Recirculated liquids from FL to IPU (96% of FL)	*173*	Lit/ton FORSU	2.70	Ton/dia				
FL Coarse solids & sands (4 of FL%) rejects	*7.2*	kg/ton FORSU	0.11	Ton/dia				
Recirculated lixiviates (from MESB to IPU)	125.46	Lit/ton FORSU	1.96	Ton/dia	1,263.60	t/a	105.30	Ton/month
Water effluent from the IPU used as biofertilizer	*14.91*	Lit/ton FORSU	0.23	Ton/dia				
	1,000.0		15.59					
Energy Information								
Electrical consumption	*24*	kWh/ton FORSU	374.40	kWh/day	135.60	MWh/a	***11.30***	MWh/month
Heat used internally	0.00		0.00			kWh/a		
Electricity for Mechanical Treatment	NA					kWh/a		
Diesel consumption	NA				0.00	l/a	There is no diesel consumption acc	
Diesel fo Mechanical Treatment	NA					l/a		
Energy used and produced								
Biogas produced TMethar	***55***	Nm^3/ton FORSU	858.00	Nm^{3}biog/day	309,552.00	Nm^3/a	***25,796.00***	Nm^{3}biog/Month
Biogas produced in the digesters	41	Nm^3/ton FORSU	643.00	Nm^{3}biog/day	231,077.00	Nm^3/a		
Biogas produced by the IPU	14	Nm^3/ton FORSU	***215.00***	Nm^{3}biog/day	78,475.00	Nm^3/a	6,450.00	
Electricity produced (generation capacity)	***91***	kWh/ton FORSU	1,419.60	kWh/day	518,154.00	kWh/a	***42.40***	MWh/month
Electric power (installed capacity)	3.80	kW/ton FORSU			***60***	kW		
Heat produced (generation capacity) inactive	412	kWh/ton FORSU	6,433.33	kWh/day	2,316,000.00	kWh/a	***193.00***	MWh/month
Heat power (installed capacity)					***269***	kW		
Biomethane (production capacity) (60%)	33.68	kWh/ton FORSU	525.47	Nm^{3}biog/day	189,168.00	Nm3/a	***15,764.00***	NM3/month
Methane leakages	0.6	NM3/Ton FORSU	8.58	m3/day	3095.52	Nm^3/a	1%	
Electricity produced available	67	kWh/ton FORSU	1,045.20	kWh/day	**374,400.00**	kWh/a	***31.20***	MWh/month
Heat potentially produced		kWh/ton FORSU	6,433.33	kWh/day		kWh/a		MWh/month

General Information	**Facts**		
Enclosed	Yes		
Type of fermenters	Batch		
Biological Process steps	1		
Digestate separation	Yes		
Digestate storage	Yes		
Post composting	Yes		
Mobil Machines neccesary	Yes		
Excess Water consumption	No		
Temperature range	30-38 °C	Mesophilic	
Population serviced	25000	inhabitants	
High calorific value of Biogas	5.5	kWh/m3	*search citation
High calorific value of Biomethane	11.06	kWh/m3	
Massa especifica media	560	kg /m3 FORSU	
Total Solids	215	kgST/ton FORSU	
Volatile Solids	190	kgSV/ton FORSU	
SV/ST	0.88		
Fermentation specifications			
Storage of the input	Flat storage		
Processing	Impurities off		
Machinery Contribution	Wheel loader/others		
Mixingtank	No		
Batch	Yes		
Fermenter position	Garage standing		
Recirculation of Liquid digestate	Yes		
Project footprint	200 m2 (patio)		
Time of biodigestation process	30 days		
Loading rate	15.6	Ton/day	
Postprocessing	Composting for 20 to 40 days		
Quantities of oils used	N/A		
Measurement of gas emissions	N/A		
Others	N/A		

Annex I. Overall GHG emissions and mitigation of WAD and DAD treatment plant

Direct emissions due to energy consumption

Electricity consumption & production

	AD1		*AD2*	
	kWh/day	kWh/a	kWh/day	kWh/a
Electricity consumed	700.00	255,500.00	374.40	135,600.00
Biogas produced	*kWh/day*	*Nm³/a*	*kWh/day*	*Nm³/a*
	0	58,400.00	4,719.00	309,552.00
Electricity production	*KWh/a*		*KWh/a*	
	73,000.00		518,154.00	

Emission Factors for consumption and fugitive gases

Emissions per 1 kWh of electricity consumed for Brazil (Ecometrica, 2011)

Electricity	0.1099	*kgCO2*	2.12E-06	*kgCH4*	6.41E-07	*kgN2O*

Gas	***100-year GWP***	
CH4	28	
N2O	265	IPCC (2014)

density of gas	1.977	kg per M3
density of CH4	0.75	kg/m³

GHG Emissions for electricity consumption and fugitive gases per year

	AD 1			
	kgCO2	*kgCH4*	*kgN2O*	
Electricity	28,081.34	0.54	0.16	
Methane leakages	-	438.00	-	
	28,081.34	***438.54***	***0.16***	*Kg/a*
	AD 2			
Electricity	14,903.44	0.29	0.09	
Methane leakages	-	2,321.64	-	
	14,903.44	***2,321.93***	***0.09***	*Kg/a*

CO2 Equivalent emissions for electricity consumption and fugitive methane

	CO2	**CO2eq. from CH4**	**CO2eq. from N2O**	**TOTAL CO2 Eq.**			
AD1							
	28,081.34	12,279.14	43.41	40,403.89	kg/a	***201.26***	***kg CO2 eq. /ton FORSU***
AD2							
	14,903.44	65,013.95	23.04	79,940.44	kg/a	***14.04***	***kg CO2 eq. /ton FORSU***
	182,500.00						

OFMSW		
AD1	0.55	ton FORSU/day
	200.75	ton FORSU/annum
AD2	15.6	ton FORSU/day
	5694	ton FORSU/annum

Direct emissions due to electrical energy production and biomethane

GHG´s	***CO2***	116,362.00	825,937.48	kg/a
	CH4	66.89	474.78	kg/a
	N2O	3.48	24.73	kg/a
Pollutants	***CO***	66.89	474.78	kg/a
	SO2	34.89	247.68	kg/a
	NOx	20.83	147.88	kg/a
	NMVOC	2.79	19.78	kg/a
	(CH2O)	3.68	26.11	kg/a

	EF = Direct emissions in air of internal	
	CO2,bio (kg)	1.594
	CObio (mg)	916.3
	N2O (mg)	47.73
	CH4,bio (mg)	916.3
	NOx (mg)	285.4
	NMVOC (mg)	38.17
	Pt (ng)	133.6
Di Maria	SO2 (mg)	478
Paolinin, 2018	CH2O (mg)	50.4

Option 1. CO2 emissions from biomethane refining (38% of CO2)

CO2(neutral)			*TOTAL CO2 Eq.*		
AD1					
-	kg/a	-	kg/a	-	*kg/ton FORSU*
AD2					
646,963.68	kg/a	-	kg/a	*113.62*	*kg/ton FORSU*

Option 2. CO2 Equivalent emissions for electrical energy production in CHP

CO2 (Neutral)	***CO2 from Ch4***	***CO2 eq. from N2O***	***TOTAL CO2 Eq.***	
AD1				
116,362.00	-	923.34	***4.60***	***kg/ton FORSU***
AD2				
825,937.48	-	6,553.84	***1.15***	***kg/ton FORSU***

These emissions might be considered neutral since they are realeased from the CO2 already captured by the biomass

Emissions saved due to energy production

***

Energy production in kWh/a

		AD1	AD2	
Option 1	Biogas	0.00	1,702,536.00	KWh/a
	Biomethane	0.00	2,092,198.08	KWh/a
		34,164.00	189,168.00	Nm3/a
Option 2	Electricity	-	518,154.00	KWh/a
	Heat	-	2,316,000.00	KWh/a

Emissions saved due to energy production

AD1

		kgCO2	*kgCH4*	*kgN2O*	
Option 1	Biomethane	-	25,623.00	-	
			25,623.00		***kg/a***
Option 2	Electricity	-	-	-	
	Heat	-	-	-	
		6,762.99	***0.13***	***0.04***	***kg/a***

AD2

		kgCO2	*kgCH4*	*kgN2O*	
Option 1	Biomethane	-	141,876.00	-	
			141,876.00		***kg/a***
Option 2	Electricity	48,003.67	0.92	0.28	
	Heat	214,562.67	4.13	1.25	
		262,566.34	***5.05***	***1.53***	***Kg/a***

Emission Factors for energy generated

Emissions per 1 kWh of electricity generated (Ecometrica, 2011)

Electricity	*0.092643638*	kgCO2	*1.78354E-06*	kgCH4	*5.4043E-07*	kgN2O

Gas	*100-year GWP*
CH4	28
N2O	265

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Saved CO2 equivalent emissions from energy production

	CO2	*CO2 Eq. from CH4*	*CO2 Eq. from N2O*	*TOTAL CO2 Eq.*	
	kg/a			kg/a	kg /ton OFMSW
AD1					
Option 1	-	717,444.00	-	*717,444.00*	***3573.82***
Option 2	6,762.99	3.65	10.45	*6,777.09*	***33.76***
AD2					
Option 1	-	3,972,528.00	-	*3,972,528.00*	***697.67***
Option 2	262,566.34	141.54	405.89	*263,113.76*	***46.21***

Total savings reference	500 kg of CO2 Eq./ton OFMSW

Overall saving CO2 Emissions potential

Overall GHG saving potential and CO2 saving ratio

	CO2 eq. Emitted		***CO2 eq. Saved***		***Saving potential***		***Ratio***
AD1	kg/a	kg/ton OFMSW	kg/a	kg/ton OFMSW	kg/a	kg/ton OFMSW	
Option 1	40,403.89	201.26	717,444.00	3,573.82	677,040.11	***3,372.55***	**6%**
Option 2	41,327.22	205.86	6,777.09	33.76	-	**-**	-
AD2							
Option 1	79,940.44	14.04	3,972,528.00	697.67	3,892,587.56	***683.63***	**2%**
Option 2	86,494.28	15.19	263,113.76	46.21	176,619.48	***31.02***	**33%**