**University of São Paulo
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**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
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1. Digestão anaeróbia 2. Bioenergia 3. Biogás 4. Avaliação ambiental 5. Fração orgânica de resíduos sólidos urbanos 6. Política pública 7. Gestão de resíduos I. Título

RESUMO

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

Tecnologias de digestão anaeróbia (DA) foram desenvolvidas e implementadas no Brasil e no México para tratar a fração orgânica de resíduos sólidos urbanos (FORSU). No entanto, 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 anaeróbico úmido (WAD) em Foz de Iguaçu e um digestor anaeróbico 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 o uso de água e recursos, geração de bioenergia, e mitigação de emissões de gases de efeito estufa, há uma eficiência significativamente maior no 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 em uma série de diretrizes e recomendações de 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 práticas tradicionais de disposição de resíduos orgânicos em lixões e aterros sanitários. Esta pesquisa prova que a DAD pode contribuir de forma notável 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 CO₂ Eq. 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

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 developed 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 organic fraction of the municipal solid waste (MSW) and agricultural residues 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 proliferation 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 proliferation 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. 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, 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 the case of AD. 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. It uses 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. 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, is comprised 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].

Figure 1. Map of Brazil northeast states and semi-arid 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 [7]. 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 [8]. 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) [8]

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.

CONCLUSIONS

In Brazil and Mexico, every year, millions of tonnes of urban solid residues are generated. Of the total, the organic fraction (OFMSW) reaches over 50% in both cases, which presents an excellent potential for its adequate treatment and production of bioenergy. Biotechnologies have already been developed and implemented for this purpose; nevertheless, there is still a long way to suffice their waste treatment needs significantly, ever-increasing fertilizers and energy demands. Hence, the organic fraction of the municipal solid waste is not sufficiently recognized as a valuable resource with significant energy and resource potential, and biotechnologies, such as anaerobic digestion (AD), are still largely unused.

The primary purpose of this research was to discover the real advantages and disadvantages of dry anaerobic digestion (DAD) and wet anaerobic digestion (WAD) technologies for the treatment of OFMSW in Brazil and Mexico; finding the keystones to foster their implementation in both countries. The research focused on three main specific objectives: The first one was to understand the state of the art of OWtE technologies in Latin America and the Caribbean (LAC) countries, and – more specifically – the status of DAD in Brazil and Mexico; the second one was to detect the technical and environmental benefits and disadvantages of DAD and WAD technologies, based on the comparison of two case studies in Brazil; and thirdly, to propose the policy guidelines and recommendation for implementing AD, and more specifically DAD technologies, based on the existing regulatory framework in both countries.

The first objective allowed the research 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.

The second research phase targeted to compare the performance of two existing biodigestion plants - one operating under dry digestion and the other as a wet digestion system - in Brazil as case studies to determine their pros and cons regarding their effects in water savings, waste management, nutrients recuperation, energy generation, and GHG mitigation potential, delimited by their system boundaries.

Firstly, 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 crops or plantations.

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 (170.18 m³ per tonne OFMSW for the AD1 compared to just 33.68 m³/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. Consequently, even when AD1 is much smaller and less complex, it consumes more electricity than AD2. The energy efficiency is represented by the energy ratio, which shows that for the AD2, 7.9% 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.

Regarding GHG mitigation potential, results demonstrate the efficiency of wet systems, considering their significant biogas production rates. AD1 can save up to 3,573.82 kg CO₂ Eq./tonne OFMSW, while AD2 around 697.67 kg CO₂ Eq. /tonne OFMSW; this is 5.12 times more. However, when it comes to the plant's direct emissions due to its electricity consumption and CH₄ leakages per treated tonne of OFMSW, AD2 emits far fewer GHG's. With 14 kg CO₂ Eq./tonne OFMSW for AD2 and 201 kg CO₂ Eq./tonne OFMSW for AD1, the DAD system emits only around 7% (or 14.3 times less) of the total emitted by the WAD 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 CO₂ Eq. The AD1 can reach a saving potential of 677,040.11 kg CO₂ Eq. yearly when biomethane is produced.

Furthermore, the CO₂ Eq. savings ratio was determined, which demonstrated that for AD1, 6% of the total CO₂ Eq. saved are emitted via electricity consumption and CH₄ losses. For the AD2, only 2% of the total CO₂ Eq. potentially saved is emitted. These results also show the effectiveness of the dry systems, demonstrating that it can save much more emissions than what it emits.

Thus, these results help conclude that even when the WAD system offers advantages of water and resource savings, energy generation, and CO₂ Eq. 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, to propose the policy guidelines and recommendations for implementing AD and DAD technologies in Brazil and Mexico, this research phase carried out an objective document analysis of the current governmental policies, regulations, and governmental actions regarding treating OFMSW through anaerobic digestion technologies. Together with a series of interviews and questionnaires to key actors, researchers, and public policy specialists, the aim was to identify the limitations, challenges, and

opportunities to apply AD on the existing regulatory framework and from a governmental perspective. The results are as follows:

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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