Assessment of a comprehensive municipal waste-to-energy dry anaerobic digestion process for the province of Sabana Centro (Colombia) combining technical and participatory approaches

Doctoral Thesis

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Abstract

Recently, there is a growing tendency in developing countries to build and consolidate stronger solid waste management systems. However, the authorities and police-makers are still struggling to use waste as a resource to generate renewable energy. Colombia has experienced reasonable economic growth over the past 20 years backed with an increase in waste generation. Nonetheless, waste management is still a challenge for the country. A few initiatives are being implemented nowadays in small municipalities to recover the organic fraction of municipal solid waste. In Sabana Centro, a small province in Colombia, six municipalities are currently implementing pilot plans to recover organic waste, two have at least two organics collection routes and send them to compost processes, and one of them (Cajicá) retrieves all the organic fraction and produce soil amendments. These facts are strong evidence that there is a growing interest in the province to implement technologies to recover organic waste. In this multidisciplinary thesis, an assessment of a waste-to-energy process for Sabana Centro by using dry anaerobic digestion and participatory approaches is proposed. First, the most relevant factors that affect municipal solid waste management systems in Colombia were outlined through a combined impact analysis and participatory methodology. Then, dry anaerobic digestion of organic fraction of municipal solid waste using samples from two municipalities in Sabana Centro was evaluated to define possible strategies to increase biogas and methane production. Both strategies were biological pretreatment using white rot fungi and co-digestion with municipal grass waste. Later, an opportunity was found to apply participatory approaches to design a dry anaerobic plant for Sabana Centro. A novel Anaerobic Digestion Participatory Methodology (ADPMDesign) was proposed to involve relevant stakeholders at different stages of the design process. During the present study, five drivers of change were found; shifts that will change municipal solid waste in Colombia. In the first place, the implementation of waste-to-energy technologies is essential to support municipal solid waste management. An effective source separation of waste is directly linked to a successful waste conversion process. Hence, public awareness must be encouraged with the help of strategies such as television, social media, and education campaigns. Moreover, the government of Colombia should dedicate efforts to develop programs in collaboration with the private sector and international organizations to reduce the high cost and risk of investment in waste treatment technologies. Public-private partnerships could foster the inclusion of the private sector in the construction and operation of waste treatment facilities. Finally, R&D projects in the academic sector can increase technical capacity in waste-to-energy. The identified drivers motivated the study at laboratory and pilot scales of dry anaerobic digestion processes using local waste. The results from laboratory and pilot scale experiments have proven that anaerobic digestion of organic fraction of municipal waste as a single substrate is not recommended for Sabana Centro, as the accumulation of volatile fatty acids caused reactor failures. The combination of municipal grass waste is a successful strategy to improve methane and biogas yields at mesophilic conditions. Meanwhile, fungal pretreatment is not recommended for these mixtures. Through the application of ADPMDesign methodology with relevant stakeholders, a process design for a biogas power plant that process the organic fraction of municipal solid waste from the eleven municipalities of Sabana Centro was developed. The implementation of ADPMDesign supported process engineering, reducing the possibility of operational incompatibilities due to the lack of knowledge of the context of implementation. The results found during this project will be useful for two different groups of stakeholders. First, the research community in anaerobic digestion will have a novel methodology that can be applied to design a biogas plant from a collective perspective. Moreover, it can benefit from the knowledge obtained through the evaluation of strategies to improve methane production from samples of OFMSW with different characteristics. Secondly, through the results from this study, stakeholders from Colombia and Sabana Centro are provided with specific guidelines to implement dry anerobic digestion in Sabana Centro and Colombia.

Evaluación de un proceso integral residuo-a-energía por medio de digestión anaerobia seca en la provincia de Sabana Centro (Colombia) combinando enfoques técnicos y participativos

Resumen

En la actualidad los países en vías de desarrollo se encuentran en la búsqueda de construir sistemas de manejo de residuos sólidos más robustos y sostenibles. Sin embargo, todavía existe un esfuerzo creciente por ver el residuo como un recurso para generar energía renovable y productos de valor comercial. Colombia es un país latinoamericano que ha experimentado un crecimiento económico razonable en los últimos 20 años, acompañado de un crecimiento en la generación de residuos sólidos. No obstante, el manejo de estos residuos sigue siendo un reto importante en el país. Existen algunas iniciativas que están siendo implementadas en pequeñas ciudades para recuperar la fracción orgánica de los residuos municipales. Por ejemplo, el caso de Sabana Centro, una pequeña provincia en Colombia en la cual seis de once municipios implementan planes piloto para recuperar los residuos orgánicos. Dos de los municipios de Sabana Centro tiene al menos dos rutas de recolección de orgánicos, los cuáles son enviados a procesos de compostaje. Otro de ellos (Cajicá), recupera toda la fracción orgánica que genera y produce mejoradores de suelo por medio de procesos de compostaje. Estos hechos son evidencia fuerte de que existe una tendencia creciente en la provincia de implementar tecnologías que permitan recuperar la fracción orgánica. En esta tesis multidisciplinaria, se propone una valoración de un proceso residuo-a-energía para Sabana Centro (Colombia) a través de la digestión anaerobia seca y el uso de metodologías participativas. Inicialmente, se identificaron los factores que afectan el manejo de residuos sólidos en Colombia a través de un análisis de impacto combinado con metodologías participativas. Luego, se evaluó la digestión anaeróbica seca de la fracción orgánica de los residuos sólidos municipales, utilizando muestras de dos municipalidades en Sabana Centro para definir posibles estrategias para incrementar la producción de biogás y metano. Las estrategias evaluadas fueron la co-digestión con residuos de poda y el pretratamiento biológico de los sustratos utilizando dos diferentes especies de hongos. Finalmente, se encontró la oportunidad de utilizar metodologías participativas para diseñar una planta de biogás para Sabana Centro. Esto se logró a partir del diseño de una metodología participativa llamada ADPMDesign que permite el acompañamiento de diferentes stakeholders en diferentes etapas del diseño conceptual del proceso. Durante la presente investigación se identificaron cinco motores de cambio que impulsarán cambios positivos en el manejo de residuos actual en Colombia. Inicialmente, se concluyó que la implementación de procesos residuo-a-energía es esencial para apoyar la transición a manejo de residuos sólidos más sostenibles. Para esto, es indispensable la implementación de políticas de separación en la fuente que permitan obtener los residuos orgánicos previamente separados. Se recomienda involucrar a la comunidad a través de campañas educativas, medios de comunicación y redes sociales. Además, el gobierno de Colombia debe dedicar esfuerzos para desarrollar programas en conjunto con el sector privado y organizaciones internacionales para desarrollar iniciativas que ayuden a deducir los altos costos y riesgos de inversión que hoy en día tienen los proyectos de manejo d residuos en el país. Las asociaciones público-privadas pueden promover la inclusión del sector privado en

la construcción y operación de las instalaciones de conversión de residuos. Finalmente, el gobierno debe promover proyectos de investigación y desarrollo que permitan aumentar la madurez tecnológica en tecnologías residuo-a-energía. Los motores de cambio identificados en el presente estudio, motivaron la experimentación a escala laboratorio y piloto de la digestión anaerobia seca para la producción de biogás, utilizando residuos locales. Los resultados de la evaluación a ambas escalas mostraron que la digestión anaerobia de los residuos orgánicos municipales como único sustrato no es recomendada para Sabana Centro, ya que existe el riesgo de acidificación en los reactores por acumulación de ácidos grasos volátiles. La combinación de este sustrato con residuos de poda municipal es una estrategia adecuada para mejorar la producción de metano y aumentar la estabilidad del proceso a condiciones mesofílicas. Por otro lado, el tratamiento biológico con hongos no mejoró los resultados del proceso. La aplicación de la metodología ADPMDesign con stakeholders permitió el diseño de un proceso para producir electricidad a partir de biogás producido por la degradación anaeróbica de residuos orgánicos municipales generada en los once municipios de Sabana Centro. Adicionalmente, la metodología apoyó el proceso de diseño de ingeniería, reduciendo la posibilidad de encontrar problemas operacionales por incompatibilidades que pueden encontrarse por el desconocimiento del contexto de implementación. Los resultados de este proyecto son de utilidad para dos diferentes grupos de stakeholders. Primero, la comunidad científica en digestión anaerobia tendrá una metodología que permitirá diseñar plantas de biogás con el conocimiento de los principales actores involucrados en el proceso. También puede beneficiarse del conocimiento obtenido acerca del tratamiento de la fracción orgánica de residuos municipales y las estrategias evaluadas para mejorar la producción de biogás. En segundo lugar, las autoridades de Sabana Centro y Colombia tienen por medio de los resultados de este proyecto una guía para implementar la digestión anaerobia, especialmente desarrollada para nuestro contexto.

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ACoD	Anaerobic co-digestion
AD	Anaerobic digestion
ADPMDesign	Anaerobic Digestion Participatory Methodology Design
ADVIAN	Advanced Impact Analysis
AF	Alcoholic Fermentation
AGPE	Small-scale generator (Autogenerador a pequeña escala)
AHP	Analytic Hierarchy Process
AS	Active Sum
ASOCENTRO	Asociación de Municipios de Sabana Centro
BOCR	Benefits, opportunities, costs, and risks
CND	National Distribution Center (Centro Nacional de Despacho)
DF	Dark Fermentation
ESCO	Energy Service Companies
EU	European Union
FDN	Financial National Development (FInanciera de Desarrollo Nacional)
GHG	Green House Gases
GNI	Gross National Income
IF	Impact Factor
JBB	Botanical Garden of Bogotá (Jardín Botánico de Bogotá)
LFGRS	Landfill Gas Recovery Systems
KPI	Key Performance Indicators
MBT	Mechanical-Biological Treatment
MEC	Microbial Electrolysis Cell
MFC	Microbial Fuel Cell
MGW	Municipal Grass Waste
MSW	Municipal Solid Waste
NEP	National Energy Plan (PEN)
NCRE	Non-conventional Renewable Energy
OFMSW	Organic Fraction of Municipal Solid Waste
PLC	Programmable Logic Controller
PS	Passive Sum
PPP	Public-Private Partnership
SGD	Sustainable Development Goals
SIN	National Integrated System (Sistema Interconectado Nacional)
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids
WtE	Waste-to-energy
WRF	White Rot Fungi

Chapter 1

Literature review

1.1 Introduction and problem to solve

Nowadays, there is a global interest in the transition towards a sustainable world. Biomass energy systems represent an important portion of the total renewable energy that is generated globally. Around 7-10% of renewable energy is provided by biomass sources (Jin et al., 2019). A sustainable society entails new ways to transform and use biomass resources for energy purposes. The use of household, animal and other sources of waste is an example. Waste generation is an issue of public health concern, especially in developing countries, where waste management is poor and there is a lack of development planning. According to World Bank reports, Municipal Solid Waste (MSW) generation per year is expected to rise to 2.2 billion tons by 2025 (World Bank Group, 2018). As a result, scientists and policy makers worldwide are dedicating efforts to find more sustainable means of waste disposal and to develop technologies that utilize waste as a resource in energy production (AlQattan et al., 2018). The United Nations General Assembly support the transition to more sustainable societies through Sustainable Development Goals (SDG); in the case of waste treatment opportunities, SDG7 (ensure access to affordable, reliable, sustainable, and modern energy) and SDG12 (ensure sustainable consumption and production patterns) play a key role.

On the one hand, developed countries, for instance those that are part of the European Union (EU), are currently adopting circular economy models to achieve SDGs, considering long-lasting design of products, maintenance, repair, reuse, and recycling to prevent waste generation. Circular economy is an approach to economic growth in line with sustainable environmental and economic development (Korhonen et al., 2018). On the other hand, developing countries are still struggling to build strong waste management systems. Due to a lack of source separation policies and practices, the organic fraction of municipal solid waste (OFMSW) represents an environmental problem since it might produce greenhouse gas (GHG) emissions having an impact on climate change (Cremiato et al., 2018), and a health issue for populations surrounding the area of disposal. Leaks may contaminate soils and water streams, mismanaged waste disposal can cause landscape deterioration, local water, and air pollution, as well as littering (Vinti et al., 2021). OFMSW represents the part of household waste that consists of food waste and grass waste. Among available processes to treat OFMSW, anaerobic digestion (AD) is the next preferred option when recycling efforts are exhausted due to its low environmental impact (Papargyropoulou et al., 2014). Accordingly, it is important to develop systems to reduce waste production and to promote the use of waste-to-energy technologies (WtE). These systems have the potential to enhance the transition from waste disposal to re-use, recycle and energy generation.

Colombia is one of the fastest growing economies in South America. MSW is potentially a valuable source in Colombia for energy generation. The population produces 15,600 tons of residential waste every day, an average of 1 kg per person daily, with an organic fraction of around 51% according to the Public Service Administrative Unit of Bogota (UAESP[1]) (UAESP, 2011). Waste generation in Colombia is growing every year and by 2020, only 15% of total waste was recycled (Holland Circular Hotspot, 2021). Nonetheless, few efforts have been done to take advantage of MSW, not only from the energy perspective but also from the by-products that are produced in the process of energy generation, e.g., fertilizers. Waste management is still a big challenge for the country and a difficulty has been found in obtaining pure food waste for future processing hindering the implementation AD processes for energy recovery.

AD is a series of biological processes in which different microorganisms break down complex molecules to produce gas in the absence of oxygen. AD has considerable research due to emerging concern for energy security and environmental protection, however, its implementation is still low in developing countries (Fan et al., 2017). There are challenges in AD, especially when dry AD processes are implemented, such as difficulty in starting-up the process, longer stabilization periods and process inhibition due to the formation of inhibitory compounds (Panigrahi and Dubey, 2019; Schievano et al., 2010). Chemical characteristics of OFMSW make it difficult to degradation by enzymes and microorganisms, and susceptible to

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[1] UAESP, in Spanish Unidad Administrativa de Servicios Públicos

inhibitions during AD. Additionally, OFMSW composition depend on local source-separation policies and affect production of gases such as hydrogen and methane from biological processes (Alibardi and Cossu, 2015). Subsequently, it is important to study waste characteristics and composition and their influence on AD processes at lab and pilot-scales. Different pretreatment techniques and other strategies can be helpful to improve AD of OFMSW.

Co-digestion processes are used as a strategy to deal with inhibitions during dry AD of OFMSW (Schievano et al., 2009). Co-digestion consist of the treatment of two or more substrates, resulting higher methane yields. Hence, it can provide feasible and sustainable waste treatment strategy (Jiang et al., 2019). For OFMSW, co-digestion with different types of sludges using continuous stirred tank reactors and batch reactors had been studied at mesophilic and thermophilic condition. Improvements in biogas and methane yields were found in many studies when co-digestion was performed with sewage sludge and waste activated sludge (Tyagi et al., 2018). Additionally, when co-digestion was performed with different types of animal waste such as cattle manure, slaughterhouse waste and slurries, increases on biogas yields around 9-35% were reported and up to 62.3% in methane contents (Tyagi et al., 2018). There are also a few studies regarding co-digestion with different substrates such as paper waste, agricultural waste, and yard waste with promising results. However, more studies are needed to define improvements in AD processes using co-digestion of agricultural or yard wastes with OFMSW.

The OFMSW is a heterogeneous mixture, and its composition and physicochemical parameters depend on many aspects such as climate condition, geographic region, living standards, season, strategy of waste collection and human activities. Additionally, the contents of yard waste are extremely variable in different parts of the countries (Panigrahi and Dubey, 2019). Biogas production from substrates strongly depend on chemical characteristics, especially on the pH, total and volatile solids, and elemental constituents like C, H, N and S. Relevant variations on OFMSW chemical parameters among different studies around the world are reported (Panigrahi and Dubey, 2019), this highlights the importance of evaluating AD processes at laboratory and pilot scales prior to building and operating municipal AD plants to determine methane yields, process stability, and specific pretreatment requirements.

Pretreatment of substrates is another strategy frequently used to improve the efficiency of AD processes with the aim of increasing accessibility of the organic matter (André et al., 2018). For OFMSW, physical and thermochemical pretreatments are extensively implemented meanwhile other methods such as biological, ozone, and ultrasound pretreatments are still to be materialized at pilot and full scales (Ariunbaatar et al., 2014; Panigrahi and Dubey, 2019). Biological pretreatments consume less energy and chemicals than other methods and having lower environmental impacts (Li et al., 2019). Biological pretreatments improve digestibility of complex waste by breaking the covalent cross linkages and non-covalent forces between hemicellulose and lignin, increasing the surface area of particulate (Mustafa et al., 2016; Ning et al., 2015; Panigrahi and Dubey, 2019). Biological pretreatments imply the use of bacteria, fungus, and enzymes.

AD has an essential role in the improvement of solid waste management strategies, especially in developing countries in which the organic fraction represents the majority of MSW (Panigrahi and Dubey, 2019). However, its implementation in developing countries is still low mainly due to the lack of specific knowledge about waste related issues and its elevated capital investments (Abdallah et al., 2020; Franceschi et al., 2022). Subsequently, it would be helpful to design dry AD facilities from a collective perspective, involving different stakeholders' knowledges and skills in the designing processes (Van den Burg et al., 2016). In the field of engineering, participatory approaches have been applied to support different design activities (Sanders and Jan Stappers, 2008). Nonetheless, to the author's knowledge, participatory design approaches have not been applied to support process design of a municipal dry AD plant that meets local needs. In this study the authors identified an opportunity to design AD facilities to treat municipal waste considering specific needs of end-users and stakeholders.

This study draws on the principle that a better understanding of the design of a WtE process can be gained through the combination of technical evaluations and participatory approaches. As a result, the aim of this project is to assess a comprehensive municipal WtE process that considers dry AD to treat source separated OFMSW in Sabana Centro, Colombia. The first chapter of this document presents the introductory concepts of the study: introduction, research question, key concepts, state-of-the-art, and objectives. Then, the second chapter outlined the context of implementation with an extensive study of the factors affecting MSW management in Sabana Centro. In the third chapter, biogas and methane production were evaluated at laboratory scale using samples of OFMSW from Sabana Centro, strategies such as co-digestion and biological pretreatments were explored. Finally, a participatory design methodology was proposed to design a municipal dry AD plant for Sabana Centro, including relevant stakeholders in different stages of the design process. Mass and energy balances, process diagrams, and the evaluation of different production scenarios from a financial perspective were developed to handle local authorities a suitable AD solution.

1.2 Definition of key concepts

1.2.1 Organic Fraction of Municipal Solid Waste (OFMSW)

OFMSW is a variable substrate; understanding of its chemical, physical and compositional aspects is necessary to implement techniques such as anaerobic digestion. Quality of biogas and digestate and stability of the reactor are influenced by these aspects. OFMSW is a heterogeneous mixture of organic and mixed waste, it can be biodegradable and can be collected as: organic waste from source separation collection systems, mixed waste from non-source separated and mixed residue (remaining matter after biowaste collection). OFMSW in the United States is defined as a mixture of food waste, garden waste and paper, in the European Union is a mixture of park, garden and kitchen waste. The composition of OFMSW depend on climate conditions, geography, living standards, human activities, waste management strategies and season (Panigrahi and Dubey, 2019).

The density of the feedstock is a parameter that influences the performance of anaerobic digestion of OFMSW, feedstocks with higher densities present higher biodegradability and less amounts of unwanted materials (Panigrahi and Dubey, 2019). Additionally, parameters such as total solids (TS), volatile solids (VS), Kjeldahl nitrogen (TKN), and specially pH of feedstocks are strongly correlated with biogas production. It has been reported that pH for OFMSW has a range of 3.9-6.2, however, optimum pH for anaerobic digestion falls within the range of 6.8-7.2. The C/N ratio should be 20:1, 30:1 or 25:1 and is essential for proper anaerobic digestion, carbon is the energy source and nitrogen have an important role increasing microbial population. C/N is also related to volatile fatty acid accumulation in the reactor. The TS must range within 11.4-27 and 15-46.3% respectively or the moisture content for dry processes should be around 60-75% (Panigrahi and Dubey, 2019).

OFMSW contains micro molecules such as carbohydrates, proteins, fat and oils and macro molecules such as cellulose, hemicellulose and lignin. Anaerobic digestion in more sensitive towards micro molecules due to the high contribution of food waste in OFMSW and towards macro molecules due to the lignocellulosic fraction. Cellulose, hemicellulose, and lignin content ranges between 12-10.7%, 5.5-17.5% and 5.4-9.6% respectively (Panigrahi and Dubey, 2019). Hemicellulose acts like a barrier around cellulose; hence, removal of hemicellulose increases biodegradability of the substrate. Lignin is the most reluctant structural component for anaerobic degradability (Sawatdeenarunat et al., 2015) and there is an inverse correlation between absolute biodegradability and lignin content. Methane production capacity of an anaerobic digestion process not only depends on the characteristics of OFMSW but also on the operating conditions and reactor types (Panigrahi and Dubey, 2019).

1.2.2 Conventional methods for the treatment of OFMSW

Conventional methods widely used for the treatment of MSW are landfilling, incineration and composting. However, they present some disadvantages related to environmental impacts, including pollution (Matsakas et al., 2017). Incineration is a thermal technology which contemplates the reaction of biomass waste with excess oxygen in a combustion process in a boiler or furnace under high pressure, the product of incineration is hot combusted gas that is used to generate electricity and heat (Tan et al., 2015a). Since incineration is based on combustion of matter, high moisture contents diminish its efficiency due to the high energy input for the evaporation of water (Mayer et al., 2019). The most suitable moisture content for waste range between 25-30% (Qazi and Abushammala, 2018).

Landfilling is a solid-based waste management technique that uses engineering principles to confine solid waste to the smallest area possible with the highest volume reduction (Tozlu and Özahi, 2016). It is estimated that more than 95% of food waste is disposed in landfills, which has catastrophic impact on the climate due to the release of methane and other GHG. There are some other disadvantages associated to production of leachate that contaminates soils and ground water, unpleasant odors and spread of pathogenic microorganisms and additionally, the chance of extract valuable products from waste is lost (Matsakas et al., 2017). Compost is another conventional technique which consider the biological decomposition and stabilization of organic waste and produces a stable final product, free of pathogens that can be applied to land (Silva-Martínez et al., 2020). However, improper composting can result in problems such as strong odors and possible generation of GHG (Mayer et al., 2019).

1.2.3 Biological waste treatment technologies

Biological processes have advantages over other technologies (incineration, pyrolysis, etc.) because they are natural processes, they need less energy input and present less harm to the atmosphere (Bres et al., 2018). Biological conversion of solid waste considers the use of microorganisms to transform organic waste to other different molecules. There are many different biological processes to treat MSW or its organic fraction and will be explained in the following sections: Landfill Gas Recovery Systems, Mechanical and Biological Treatment, AD, Alcoholic Fermentation, Dark Fermentation, Microbial Fuel Cells, and Microbial Electrolytic Cells. Figure 1.1 presents the available biological waste treatment processes and its final products.

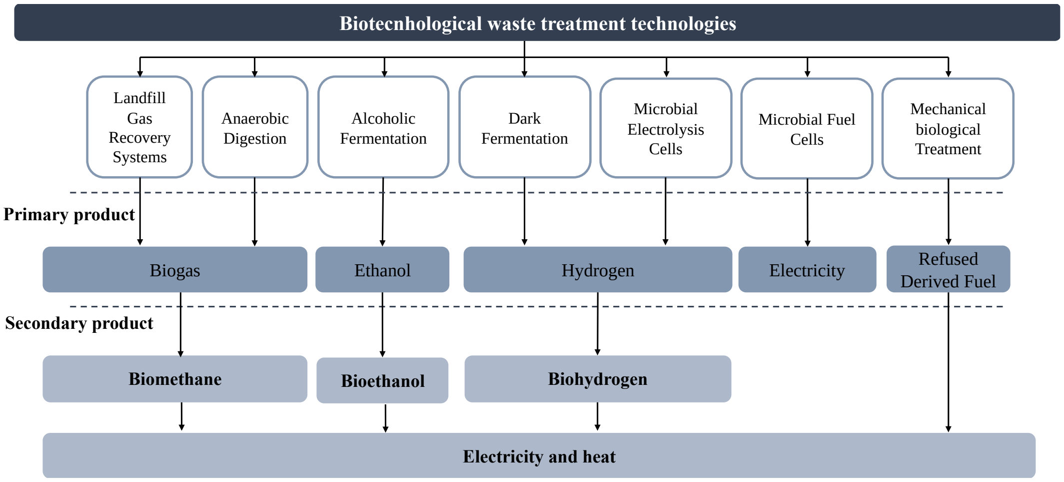

Figure 1.1.Overview of biological waste treatment technologies and their final products.

Anaerobic Digestion (AD)

AD is preferentially suited for high moisture content or semi-solid organic materials such as the OFMSW. Literature indicates that AD is the best biological treatment option for OFMSW regarding environmental and economic performances (André et al., 2018). AD is the biological transformation of organic waste into high energy value gas (biogas) and stabilized digestate by microorganisms (Panigrahi and Dubey, 2019). The technology consists of several chemical and biological processes carried out by microorganisms that requires no oxygen to survive (Mayer et al., 2019). The overall conversion process of biogas can be divided in four stages. Hydrolysis, where complex long chain organic compounds are broken down into basic molecules such as fatty acids, monosaccharides, amino acids, and related compounds. Acidogenesis, where acidogenic bacteria break down the remaining components, in this stage methane (CH_4), carbon dioxide (CO_2) and ammonia (NH_3) are produced. Acetogenesis, where simple molecules created by acidogenesis are further digested to produce acetic acid, CO_2, and hydrogen (H_2). Finally, during methanogenesis, methanogenic bacteria convert the intermediate products into CH_4, CO_2 and water (Tan et al., 2015a). The main product of the process is biogas, that is mainly CH_4 and CO_2. The amount and quality of the produced biogas depends on the organic waste used for the digestion process and process variables such as temperature, pH, and others (Krishna and Kalamdhad, 2014). The co-product known as digestate can be considered for soil amendment or fertilizer dependent on legal regulations in the region (Mayer et al., 2019).

A general AD process is presented in Figure 1.2. The substrate can be pretreated with mechanical, chemical, thermal, thermo-chemical or biological techniques to adjust operational parameters for digestion (Panigrahi and Dubey, 2019). These operational parameters depend on the substrate to digest (OFMSW, animal manure, agricultural waste, etc.). Later, anaerobic digestion is carried out. According to the total solid contents of the substrate, AD can be wet or dry. Dry AD generally occurs at solid concentrations higher than 15% and wet AD for feedstocks with TS between 0.5 and 15%. Methane is the energy source of biogas, hence, high methane content in final biogas stream is required. Biogas can be transformed through different processes into many final products: electricity, vehicle fuel and cooking fuel. Depending on biogas final use, different treatments must be applied to remove chemical compounds.

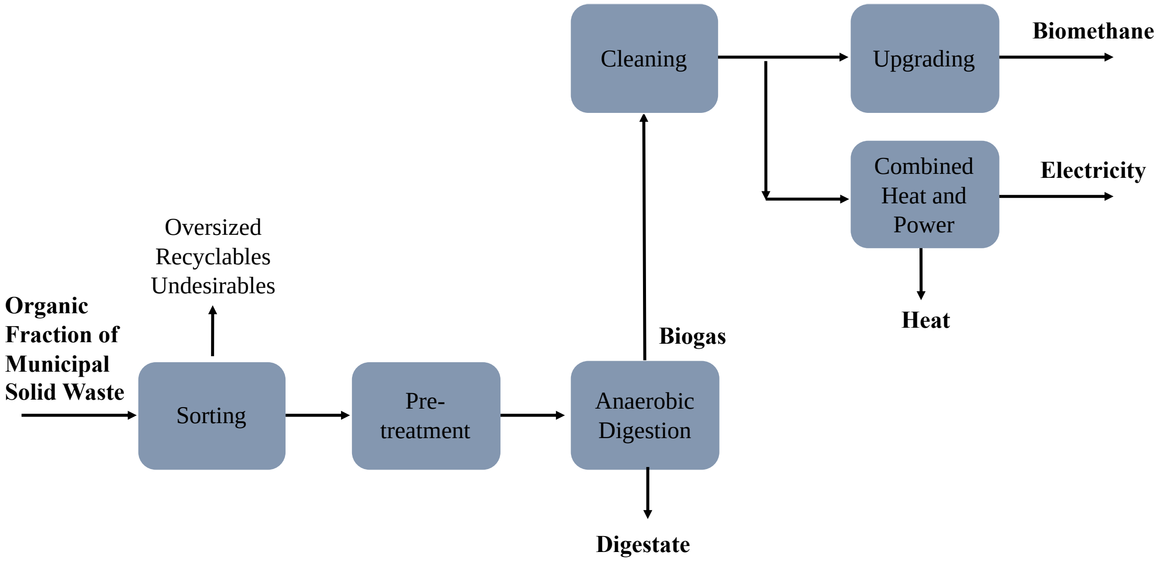

Figure 1.2. Block diagram of an Anaerobic Digestion process and its possible products.

Dry Anaerobic Digestion

Wet anaerobic digestion is the most common form in plants around the world. However, there is an increasing interest in dry AD (André et al., 2018). For substrates such as OFMSW, dry AD is recommended over wet (Krishna and Kalamdhad, 2014). During dry processes, an inoculum is an essential parameter as it conveys the microorganisms, the nutrients to the solid phase (André et al., 2018). The quality and properties of the inoculum is a vital parameter affecting the process, at industrial scales the most appropriate inoculum for a process is the sludge acclimated with the substrate and conditions of the same process (Mirmohamadsadeghi et al., 2019). Dry AD is performed in continuous and discontinuous processes in reactors without the addition of process water. Continuous digesters are loaded sequentially during the day and its operation contemplates mixing. Discontinuous processes are systems in the presence of a recirculated liquid phase to promote the development of microorganisms, distribute the moisture and nutrients and maintain temperature. In Table 1.1, a comparison of technical aspects between wet and dry AD is presented.

Table 1.1. Comparison of solid-state AD and Liquid AD systems (André et al., 2018; Ge et al., 2016)

Item	Wet	Dry
Power needs	High 20% to 30% of heat produced	Low Lower need for thermally insulated installations
Modularity and mobility	Low	High
Equipment	More critical	Less critical
Water consumption	High Dilution is necessary	Low Percolate renewal Dilution not necessary
Maintenance required	High	Low
Adaptability of substrates	Low Maximum 20% of TS	High Between 20 and 40% of dry matter TS
Load and unload of the digester	Special technologies not required	Special technologies required
Mixing	Easy	Difficult to achieve
Inhibition	Low	High due to the accumulation of VFAs
Digestate handling and quality	Post treatment is needed, and handling is complex	Easy handling and high quality
Investment and operating cost	Low	High
Process stability	Easier to intervene in the case of biological malfunction	Need to manage several digesters simultaneously

In the table TS: total solids, VFA: volatile fatty acids

1.2.4 Comparison of biological waste-to-energy technologies: relevance in Sabana Centro, Colombia

To understand the relevance of a WtE technology for a specific application a more detailed comparison is needed. The performance of the different WtE technologies depend on technical factors, such as: emission levels, energy efficiencies, type of end-use applications, the energy source, amongst others. Additionally, the selection of an appropriate WtE technology depend on the characteristics of the substrate or the waste that is required to process, its availability and the specific requirements of the implementation site. Sabana Centro has eleven municipalities and only in Cajicá an appropriate treatment of OFMSW is performed. However, a more suitable technology can be proposed not only for Cajicá, but for the remaining municipalities. A comparison of biological MSW treatment processes was performed in terms of environmental, technical, and financial aspects. Table 1.2 presents detailed information of relevant aspects for biological transformation of waste into energy.

Table 1.2.Comparison of relevant aspects of biological waste treatment processes

Technology	Feedstock compatibility	Waste segregation	Environmental impact	Technical expertise	Land use	Modular design	Capital cost (investment)	Residence time	Products	Maturity	References
Landfill Gas Recovery System (LFGRS)	High compatibility with MSW	Not necessary	From waste to electricity: 2708-1524 tCO_{2e}/t waste	Medium - lack of skilled expertise to develop and maintain sanitary system	36 hectares	Not possible	3.7 MEUR (1.6 MW Power plant) 2.4 MEUR (Direct use of gas in a nearby plant) (Year: 2008)	1-3 years in landfills	Methane	Commercial	(Tozlu and Özahi, 2016)
Mechanical Biological Treatment (MBT)	MSW, commercial and industrial wet type.	Performed at the facility	MBT process (without AD): 0.161 tCO_{2e}/ t waste Biogas to electricity: 0.1-0.4 kg CO_{2e}/kWh	High – skilled personnel required	18 to 24 hectares	Possible for biological treatment	203 EUR/tpa (Database of waste management technologies)	42 to 70 days	Refuse Derived Fuel Biogas and Digestate (when combined with AD)	Commercial	(Kourkoumpas et al., 2015; Tan et al., 2015a)
Anaerobic Digestion (AD)	Preferentially suited for high moisture content	Needed	Wet: 0.05-0.3 tCO_{2e}/ t waste Dry: 0.035-0.12 tCO_{2e}/ t waste Biogas to electricity: 0.1-0.4 kg CO_{2e}/kWh	Medium - skilled personnel not required	2 hectares	Possible	Wet:208-304 EUR/tpa Dry: 320 EUR/tpa (Database of waste management technologies)	15 -30 days	Methane and digestate	Commercial	(André et al., 2018; Ge et al., 2016; Krishna and Kalamdhad, 2014)
Alcoholic Fermentation (AF)	Organic waste	Needed	0.033 tCO_{2e}/ t biomass (lignocellulosic biomass)	High- skilled personnel required	4 to 6 hectares	Possible	497 EUR/tpa (2017)	2 to 7 days	Ethanol	Commercial	(Barampouti et al., 2019)

Technology	Feedstock compatibility	Waste segregation	Environmental impact	Technical expertise	Land use	Modular design	Capital cost (investment)	Residence time	Products	Maturity	References
Dark Fermentation (DF)	Organic waste	Needed	0.20-0.46 tCO_{2e} / t biomass (Lignocellulosic biomass)	High - skilled personnel required	Not reported	Possible	Combined with AD: 342 EUR/tpa (2018)	72-18 hours pilot scale	Hydrogen	Integrated pilot system demonstrated, TRL 7 - Europe	(Lukajtis et al., 2018)
Microbial Fuel Cell (MFC)	Organic waste	Needed	0.02 tCO_{2e} / t water For waste-water treatment	Not reported	Not reported	Possible	220 EUR/m^3 for a waste-water treatment plant (2012)	Days (lab-scales)	Electricity and water	Pilot scales	(Florio et al., 2019)
Microbial Electrolysis Cell (MEC)	Organic waste	Needed	0.35 tCO_{2e} / t biomass When combined with dark fermentation	Not reported	Not reported	Possible	220 EUR/m^3 (for a waste-water treatment plant) (2012)	Days (lab-scales)	Hydrogen	Pilot scales	(Mehmeti et al., 2018)

In the table tpa: tons per year, t: tons.

To define the which biological treatment will be suitable for Sabana Centro, a screening was performed to select the most significant aspects. Considering that the eleven municipalities of Sabana Centro have different waste generation rates, the possibility of designing modular reactors is attractive. Another relevant aspect of biological waste-to-energy technologies is the maturity, developing countries should adopt existing technologies to accelerate its development process (World Bank Group, 2018). It would be useful for Sabana Centro and even for Colombia to consider a technology that has been already implemented at industrial levels, then, MECs, MFCs and DF are discarded. LFGRS are not considered as an option for Sabana Centro and Cajicá since there are no landfills in Sabana Centro. To compare the remaining technologies a scoring system was established according to different criteria. Dry and wet AD were analyzed separately due to important differences in the selected aspects. Table 1.3 presents the classification criteria for each aspect and final scoring.

Table 1.3. Classification criteria selected and its description

Aspect	Scoring System	Description	References
Source Separation	Needed (0) Not needed (1)	Source Separation would be an advantage since Sabana Centro has the goal of implementing source separation policies in the remaining 10 municipalities, following the successful experience in Cajicá.	(Kourkoumpas et al., 2015; Krishna and Kalamdhad, 2014; Matsakas et al., 2017)
Environmental Impact	High > 0.3 (0) Low < 0.3 (1)	Average environmental impact was calculated according to the results from LCA reported in Table 2 (0.3 t of CO2e per t of biomass). Values higher than the average were considered high and below the average were considered low.	(Kourkoumpas et al., 2015; Tan et al., 2015b)
Technical Expertise	Needed (0) Not needed (1)	The need for high technical expertise for the plant operation is not beneficial since it causes an increase in operational costs.	(Barampouti et al., 2019; Kourkoumpas et al., 2015; Yap and Nixon, 2015)
Land Use	Large > 7 Ha (0) Small < 7 Ha (1)	Average land use was calculated according to results presented in Table 2 (7Ha). Values higher than 7Ha were considered large and below the average were considered small.	(Barampouti et al., 2019; Kourkoumpas et al., 2015; Yap and Nixon, 2015)
Capital Cost	High > 319 (0) Low < 319 (1)	Average capital cost was calculated according to results presented in Table 2 (319 EUR/tpa). Values higher than 319 EUR/tpa were considered high and below the average were considered low.	(Kourkoumpas et al., 2015; Tan et al., 2015a)

In the table tpa: tons per year, LCA: Life Cycle Assessment

Technologies that require previous source separation of the waste would be desirable for Sabana Centro. In Cajicá, OFMSW is separated by households and businesses and the goal is that the remaining municipalities implement source separation policies as well. Low environmental impact and capital cost is also desirable. Effective waste management often represent around 20%-50% of municipal budgets, and in developing countries municipalities have other priorities (The World Bank, 2021). As a result, technologies with lower costs, smaller land uses, and low technical expertise are more attractive. Table 1.4 presents the results of the scoring process.

Table 1.4. Summary of biological waste treatment technologies and their scoring

Technology	SS	Pts	EI	Pts	TE	Pts	LU	Pts	CC	Pts	Score
Mechanical Biological Treatment (MBT)	Not needed	0	High	0	Needed	0	Large	0	Low	1	1
Wet Anaerobic Digestion (WAD)	Needed	1	High	0	Not needed	1	Small	1	Low	1	4
Dry Anaerobic Digestion (DAD)	Needed	1	Low	1	Not needed	1	Small	1	High	0	4
Alcoholic Fermentation (AF)	Needed	1	Low	1	Needed	0	Small	1	High	0	3

In the table SS: source separation, EI: environmental impact, TE: technical expertise, LU: land use, and CC: capital cost.

To conclude, AD is the most suitable waste treatment technology for Sabana Centro, Colombia considering aspects such as source separation, environmental impact, technical expertise, land use, and capital cost. Followed by AF, and lastly MBT. Dry and wet AD presented the highest score. However, dry AD is more suitable for substrates such as the OFMSW and present many advantages against wet AD. On the other hand, the main difference between AD and AF is the fuel produced, AD produces biogas and AF bioethanol. Ethanol has been widely used in vehicles after blending with gasoline at different ratios without the need of complex modifications in conventional cars (Matsakas et al., 2017). Nowadays, bioethanol is produced by the corn starch-based technology (or other cereals) which is expensive, and the cost of bioethanol is high compared to fossil fuels (Beschkov, 2017). The main disadvantages of AF when compared to AD are the need of significant heterogeneity in waste, the emission of possible toxic contaminants, and the complexity of the process to make sugar monomers available to the microorganisms. This complexity requires a high technical expertise to operation and maintenance activities. Finally, the least recommended technology is MBT. MBT plants are designed to treat MSW without any source separation (Beschkov, 2017). Another alternative is to use the refused derive fuel for combustion, increasing the environmental impact associated to the technology.

1.2.5 Anaerobic co-digestion

Anaerobic co-digestion (ACoD) is the combination of two or more substrates to perform anaerobic digestion. This strategy provides better availability and balance of nutrients for adequate microbial growth, dilution of toxic compounds, moisture adjustment, and a better buffering capacity. ACoD have positive effects on process efficiency increasing biogas generation due to improved stability (Tyagi et al., 2018). The most relevant benefits from ACoD are increase methane yields, improved process stability, and better handling of wastes (Figure 1.3). The co-substrate should favor positive synergism by balancing the deficient components and overcome inhibitions.

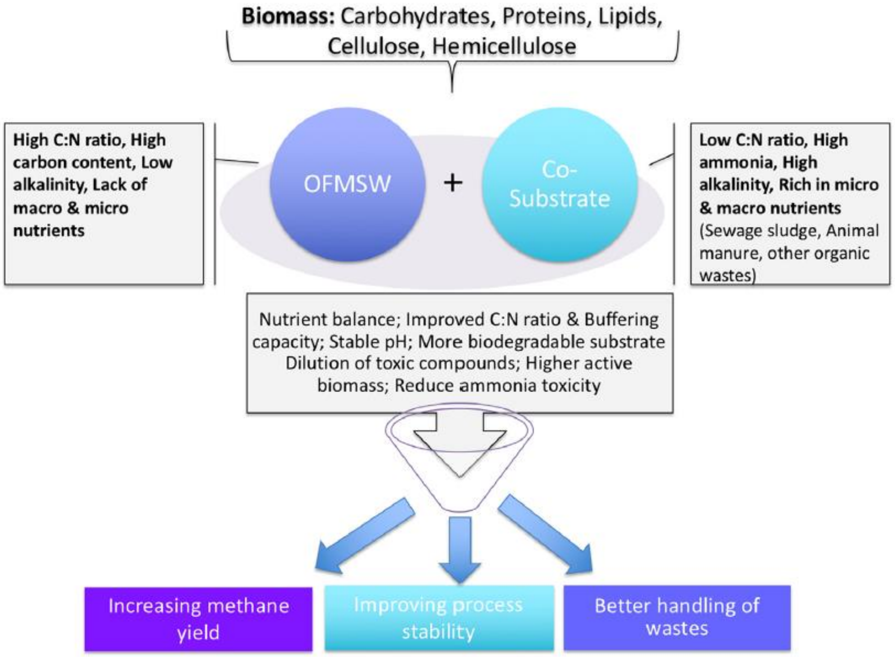

Figure 1.3. Principal benefits of ACoD of OFMSW (Tyagi et al., 2018).

1.2.6 Pretreatments: advantages and disadvantages

Pretreatment technologies can be classified as: mechanical, thermal, chemical, biological, and combined. Many pretreatment techniques have been developed for dry anaerobic digestion; however, high costs and low efficiencies can cause low profitability and few utilizations in dry processes at larger scales (André et al., 2018). In this context, new research should be developed to approach these technological hurdles. A summary of pretreatment technologies proposed for OFMSW, advantages and disadvantages are presented in Table 1.5

Table 1.5. Summary of pretreatment technologies, advantages, and disadvantages (André et al., 2018).

Pretreatment	Advantages	Disadvantages	Mechanism	E, C, EI, DD
Mechanical	Suitable for heterogeneous OFMSW Improves mass transfer Decreases cellulose crystallinity and degree of polymerization	High power and energy requirement	Decrease the particle size, increasing the surface to volume ratio and pore volume	E:3 C: 2 EI:1 DD: Full-scale
Thermal	Destruction of hemicellulose Better than chemical pretreatments Reduction in particle size is not needed Chemicals and corrosion-resistant materials are not needed	Large amounts of water Water treatment is required downstream Chance of formation of inhibitors at high temperatures	Solubilizing refractory particles deflocculating macromolecules and improving total COD	E:2 C: 2 EI:3 DD: Bench-scale
Alkaline	Removes lignin of biomass Reaction condition is mild Decreases cellulose crystallinity and degree of polymerization	Alkaline agent acts as inhibitor during AD Duration is high Neutralizing agent is required after pretreatment	Increasing internal surface area, disrupting the lignin, and breaking the bond between lignin and carbohydrates.	E:3 C: 1 EI:3 DD: Lab-scale
Dilute Acid	Effectively removes hemicellulose and recover sugars Less quantities of neutralizing agents compared to alkaline	Chance of corrosion Inhibitors can be produced	Disrupting the hemicellulose, and breaking the covalent hydrogen bonds, and Van der Waals forces	E:2 C: 3 EI:1 DD: Lab-scale
Ozone	No chance of formation of toxic oxidants Conditions are independent from reaction temperature and pressure	Cost associated with the formation of ozone	Solubilizing and/or breaking lignin.	E:2 C: 3 EI:1 DD: Lab-scale
Biological	No chance of formation of toxic inhibitors Low environmental impact No chemicals required	Sensitive to operating conditions Duration is high High reactor size	Breaking the covalent cross linkages and noncovalent forces between hemicelluloses and lignin and increasing the surface area of particulate.	E:2 C: 3 EI:1 DD: Lab-scale
Electro hydrolysis	No chance of formation of toxic inhibitors Duration is low	High cost associated with energy requirement and electrode preparation	Solubilizing organic matter by breaking bonds among polymers.	E:2 C: 3 EI:1 DD: Lab-scale
Ultrasound waves	Green technology Room temperature and pressure Dewaterability of feedstocks is improved	Optimum conditions are substrate specific Energy intensive technique	Cavitation and chemical reactions.	E:2 C: 3 EI:1 DD: Lab-scale

In the table: AD: anaerobic digestion, COD: chemical oxygen demand, E: efficiency, C: cost, EI: environmental impact, DD: degree of development.

1.2.7 Biological pretreatment with the white rot fungi

There are many pretreatments than can be used to treat biomass prior to biological processes: chemical, mechanical, thermal, thermo-chemical, and biological. Pretreatments can increase investment and operational costs of processes, being an obstacle for commercial scale adaptations. However, among pretreatments, biological have the advantage of being less expensive and environmentally friendly (Rouches et al., 2016).

Processes to transform OFMSW usually present bottlenecks due to recalcitrant lignocellulosic materials and inhibitory compounds. Lignocellulosic materials represent a significant fraction of OFMSW and are not easily fermentable, usually a pretreatment is needed to enhance their conversion efficiency (Ebrahimian et al., 2022). Biological pretreatments include fungal, enzymatic, ensiling, and partial composting (Rouches et al., 2016). The use of filamentous fungi to pretreat lignocellulosic biomass is frequently studied. In fact, when enzymatic pretreatments are performed, commercial enzymatic cocktails are usually produced by fungi, particularly *Trichoderma* and *Aspergillus* genus (Rouches et al., 2016). The simplest process scheme consists in directly pretreat the biomass prior to its anaerobic digestion. Fungi that can degrade the main three components of biomass can be classified into white, brown, and soft rot fungi. White-rot fungi (WRF) are generally chosen as they are more efficient in delignification (Rouches et al., 2016). WRF belong to the Basidiomycota phylum and a small part of them to *Ascomycota* phylum, they have a large field of action due to their ability to decompose aromatic and xenobiotic compounds, being useful in soil remediation and water treatment. Treatment with WRF results in a bleached presentation of the substrates, hence, they are frequently used in the paper industry to bleach kraft pulp. Lignin content and/or linkages with holocellulose can limit the conversion of biomass into biofuels. Their resulted sugar yields make them a promising alternative to increase methane and ethanol production (Rouches et al., 2016).

WRF use extra-cellular enzymes that form hydrolases and a ligninolytic system comprising three major oxidizing enzymes: lignin peroxidase (LiP or ligninase EC 1.11.1.14), manganese perodxidase (MnP, EC 1.11.1.13), and lacasse (or phenoloxidases, EC 1.10.3.2). WFR can produce either one or three or them or even different paired combinations (Tuor et al., 1995). Solid state fermentations can be carried out with WRF since they increase its availability for hydrolysis. The mycelial penetration creates pores, increasing surface areas for enzymatic attacks (Rouches et al., 2016). Depending on the characteristics of the substrates and fungal growth rate, pretreatments with WRF can las for months or week. During pretreatment, WRF need oxygen for growth and for the oxidative process of delignification. Thus, delignification is sometimes enhanced with higher oxygenation rates (Rouches et al., 2016).

1.2.8 Impact Analysis

Frederic Vester in 1999 developed "the sensitivity model", an inter-disciplinary modelling approach to assist groups of experts from different reality domains to build a common language. The sensitivity model suggest that human cognition can be described by pattern recognition (Vester, 2007).

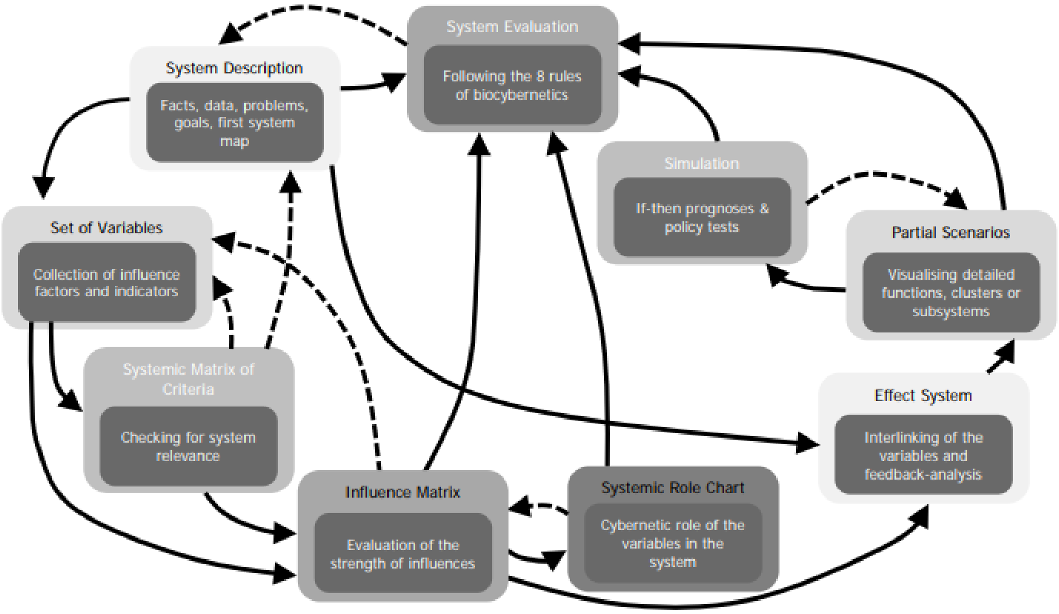

Figure 1.4. The Vester's sensitivity model (Wolf et al., 2012).

The complete methodology of Vester's sensitivity model is presented in Figure 1.4. The process starts with the system description, in which facts, data, problems and goals are mapped. In this step, the system is described in terms of the key elements or variables that are more relevant (Moreno et al., 2014). Then, the definition of system variables is performed using system description as baseline. During steps three and four, criteria and influence matrices are used to define the relevance of each variable on the system and to evaluate the strength of influences of each variable. In these steps, the relations between selected variables are established to determine the magnitude of the influences among them. Both steps are of great relevance since they reflect the behavior of the system (Moreno et al., 2014). Finally, during steps 5-9 the simulation of the process in performed (Kunze et al., 2016). As part of the present study, steps 1 to 4 of the sensitivity model were carried out combined with participatory approaches to analyze Colombian MSW management system.

The impact matrix contains the information of interaction among the variables, it reflects the influence of the variable *i* on the variable j. The effects are calculated by the measurement of the pairwise effect on the variables were the others change. As variables do not influence themselves, therefore the diagonal of the matrix is full of zeros. A scale from 0 to 3 can be used to measure this effect by answering the question: if the variable x changes, how does the variable y change? (Moreno et al., 2014). Only the magnitude of the influence irrespective of the sign is considered. The impact matrix is built with the following indicators (AS, PS, Q y P). The Active Sum (AS) is the sum along rows, indicates how big is the effect of the variable on the others. The Passive sum (PS) is the sum along columns and indicates how does the variable react to changes in the system. Quotient (Q) is the ratio AS/PS and determines the dominant or influenceable a variable is, the larger the coefficient, the more active is the variable. Product (P) is the product AS*PS, determines how participative a variable is. If the product is large, the more critical is. Finally, variables are organized in a plot whose axes are PS and AD. Highly active variables will be in the upper left corner, highly reactive in the lower right, highly critical will be in the upper right and buffering in the lower left corner (Moreno et al., 2014). In this work, Vester's impact matrix was filled using participatory approaches and the results of the impact matrix were analyzed by the ADVIAN® method (Linss and Fried, 2010).

The ADVIAN method was developed by Linss and Fried (2010), it explores the indirect relationships among the variables by the calculation of three new indices: stability, criticality, and integration (Linss and Fried, 2010). The indices are calculated by using matrix multiplication methods two obtain two parameters, the indirect active and passive sum. Criticality is the geometric mean of the indirect active and passive sum. Critical factors are strongly influenced by the system and strongly influence the system. Therefore, they are not suitable for changes because the reaction in the system cannot be predicted. Stability is the harmonic mean of the relative and active sum for every variable. Stability factors control the system. Integration is the arithmetic average of the indirect active and passive sum (Wesselink et al., 2011).

1.2.9 Participatory methodologies

Participatory approaches are necessary to handle complex issues regarding multiple stakeholders and sectors (Van den Burg et al., 2016). Participation has the following objectives: defining the role of scientifically derived (systematic) and experience-derived (idiosyncratic) knowledge for making choices that affect populations; finding the most appropriate way to handle with uncertainty in the decision-making processes, and address concerns of affected people and the public (Wesselink et al., 2011). During the present study, different participatory methodologies were applied: workshops, interviews, and focus groups. Participatory methodologies are an opportunity for innovation and social learning and ensuring stakeholders commitment with social changes, creating new approaches for accomplishing established objectives. Through participatory workshops, a stronger sense of belonging is generated which encourages people to participate in the projects, even when obstacles arise; a common ground for negotiation can be created for every party involved (Acero López et al., 2019). On the other hand, Sander, and Stappers (2008) defined participatory design as an instance of co-creation as the creativity of designers and people not trained in design working together in the design development process (Sanders and Jan Stappers, 2008). In participatory design experts come together to cooperate creatively, stakeholders such as researchers, designers, potential customers, and users.

1.3 State-of-the-art

1.3.1 MSW management systems in Latin America and Colombia

Municipal Solid Waste management in developing countries is still not environmentally sustainable. Some of the most relevant issues are related to low collection coverage, inadequate collection services, burning without air and pollution control, and informal waste handling. Additionally, policies have been implemented but their application have been inconsistent. Cetrulo et al. (2018) applied a methodology in Brazil to evaluate the effect of implementing changes in the solid waste policy through key performance indicators. Results showed no improvements in the indicators studied. However, some lessons and strategies were identified and extrapolated to other developed countries (Cetrulo et al., 2018). Waste management is a critical aspect to be studied and improved from an environmental perspective in developing countries. Margallo et al. (2019) analyzed the situation of waste management specially in Latin America and the Caribbean to identify challenges and opportunities. According to the results, the most relevant challenges are the use of landfills to dispose solid waste, the integration of the informal sector, and the inclusion of WtE technologies to manage solid waste. Political stability and economic growth are both necessary to make changes possible (Margallo et al., 2019).

Circular economy has been studied in the recent literature and the concept has been discussed for decades. However, there have been few studies focused on the management of organic waste and its relationship with circular economy (Bertolucci Paes et al., 2019). Bertolucci Paes et al. (2019) performed a systematic literature review and content analysis to identify opportunities, strengths, threats, and weaknesses (SWOT) of organic waste under circular economy principles. The most relevant weaknesses were seasonality, availability, and lack of homogenization of organic waste, and lack of technical standards and regulations (Bertolucci Paes et al., 2019). Tsai et al. (2020) conducted a bibliometric analysis on MSW management as a basis for a circular economy. During their study, the authors found that Latin America and the Caribbean ranked third in the number of publications in the field of MSW management and circular economy. This indicates a recent interest in the field and room for further studies (Tsai et al., 2020). Moreover, Ferronato et al. (2021) studied strategies to improve the recycling rate of MSW in developing countries through a life cycle assessment. The authors recommended that municipalities invest in data analysis to support scientific studies and encourage recycling efforts, such as reducing the disposal of plastic materials like plastic bags (Ferronato et al., 2021)

Batista et al. (2021) emphasize the relevance of including relevant stakeholders in integrated solid waste management systems. Multidisciplinary approaches are essential to provide environmental, economic, and societal contributions to achieve eleventh and the twelfth SDG (Batista et al., 2021). In addition, Khan et al. (2022). studied the challenges, benefits, and limitations of conventional and non-conventional methods of MSE management. The study demonstrated that chemical, biological and thermal treatment methods are more effective than conventional methods. Furthermore, the authors suggest that contextual factors, such as waste generation, location, and socio-economic factors, should be considered to determine the most appropriate technology for each situation. Finally, the study highlights economic incentives as a key driver to promote WtE technologies (Khan et al., 2022). Silva (2021) studied the feasibility of implementing dry AD technologies in Brazil and Mexico, evaluating the environmental benefits and advantages, and proposed the policy guidelines for its implementation. The authors used different techniques to estimate environmental impacts and participatory approaches to detect the most relevant challenges for the implementation of dry AD (Silva, 2021).

In Colombia, Calderón Marquez and Rutkowski (2020) identified the drivers that have influenced the waste management policies in Colombia and their impact in the MSW management system. The most relevant drivers were financial sustainability and inclusive recycling, both had allowed improvements towards a more sustainable system in the country. Moreover, the main uncertainties are related to the effective inclusion of informal waste collector organizations and their financial sustainability (Calderón Márquez and Rutkowski, 2020). Finally, there is a study developed in one of the municipalities of Sabana

Centro (Chía) with the purpose of assessing the governance capacity to implement resources recovery from organic waste using participatory approaches with stakeholders. Aguilar et al. (2022) emphasized the relevance of local initiatives in resource recovery that allow experimentation and raise awareness. Moreover, the study identified a missing link of information among stakeholders and low awareness of potential benefits of recovering resources from organic waste (Aguilar et al., 2022).

It is noticeable from the literature review that there is a recent interest in studying MSW management systems from a collective perspective around the world. Latin America and the Caribbean are no exception, with research efforts being devoted to supporting more sustainable waste management in cities and countries. While there have been only two studies on this topic in Colombia in the last 5 years, the relevance of local initiatives to recover waste is being highlighted, which represents an opportunity to study MSW systems, define the context, and develop recommendations for stakeholders. Finally, the involvement of relevant stakeholders is essential as it can help familiarize them with treatment technologies and understand the benefits and challenges, allowing for their contribution to every aspect of the process. These reasons give rise to the following questions: How do these challenges, barriers, and key opportunities apply in the Colombian context? What recommendations can be formulated for Colombia to transition effectively to more sustainable waste management? How can stakeholders be involved in different stages of the research process? These questions will be answered in Chapters 2 and 4.

1.3.2 Dry Anaerobic digestion of OFMSW: ACoD and pretreatments

AD is a waste management alternative that can provide renewable energy. Is the most recommended option to treat the OFMSW in terms of economic and environmental performance (Fan et al., 2017; Panigrahi and Dubey, 2019). However, despite its benefits, AD implementation in Latin America is still low (Fan et al., 2017). Dry AD is performed when the TS content of the substrate is higher than 15%. Recently, there is an increased interest in dry AD since reactor volumes are reduced, energy consumption is lower, transport costs are reduced due to lower digested volumes, and the digestate produced are easier to handle (André et al., 2018; Jiang et al., 2019). There are some hurdles in the conversion of OFMSW into biogas. The most relevant are their heterogeneity and complex structure (Panigrahi and Dubey, 2019). Food wastes and the OFMSW present high volatile solid contents and high concentration of toxic inhibitors, leading to possible failures of the process due to severe acidification (Jiang et al., 2019; Wang et al., 2022).

Schievano et al. (2010) investigated high-solids or dry AD processes with different sources of OFMSW with different putrescibility at lab-scale batch thermophilic processes. Results demonstrated that OFMSW may be easily subjected to inhibition due to organic overloading. OFMSW samples with higher putrescibility were more susceptible to reactor failures. The authors suggest that volatile solid content and organic loading are not suitable parameters to predict overload inhibition (Schievano et al., 2010). On the other hand, Jiang et al. (2022) used a two-stage configuration to treat high VS OFMSW. The configurated consisted in a tank-type acidogenic phase and a fixed-bed methanogenic phase. Through the two-stage configuration, methane contents around 70-83% were achieved. However, the process stability is difficult to maintain at high organic load rates. Further studies are needed to understand more about process mechanisms (Jiang et al., 2022).

Two different strategies have been proposed to improve AD processes from the OFMSW, anaerobic co-digestion (ACoD) and pretreatment techniques. ACoD of OFMSW with different types of municipal sludges have been studied considering different operating conditions. Ara et al. (2015) studied ACoD of OMSW with primary sludge and thickened waste activated sludge. The results were conclusive that biogas production was enhanced through the ternary mixtures when compared to binary and individual substrates. The higher biogas yield (780 mL/g VS) was obtained for mixtures with 50:25:25 ratios, producing 136% more biogas than the expected from individual substrates (Ara et al., 2015). Borowski (2015) studied temperature phased ACoD of sewage sludge and OFMSW obtaining an overall methane production of 333 mL/g VS (Borowski, 2015). Mesophilic ACoD of OFMSW with sewage sludge was studied by Silvestre et al. (2015), mixtures showed the highest increase on methane production under stable conditions (Silvestre et al., 2015).

ACoD of OFMSW with different sources of animal waste such as cattle manure and slaughterhouse waste showed improvements on biogas and methane yields that ranged from 9 to 63%. Methane yields from 0.23 to 0.61 m^3/kg VS were reported (Cuetos et al., 2008; Hartmann and Ahring, 2005; Moestedt et al., 2016; Zhang et al., 2013). Pezzolla et al. (2017) studied the effect of recirculating the percolate during dry ACoD of pig slurry and straw. Percolate recirculation was performed once, twice or four times daily. Biogas production was enhanced when percolate was recirculated, especially with a frequency of 4 times daily. Recirculation avoided the accumulation of VFAs in the liquid fraction and a better process stability (Pezzolla et al., 2017). Finally, a few studies exploring ACoD of OFMSW with other wastes such as paper waste, card packing, silage, and yard waste are reported. Brown & Lee (2013) studied ACoD of food waste with yard waste. Results showed increased methane yields and volumes when food waste was increased to 10% and 20% of the substrate (Brown and Li, 2013). Moreover, Schievano et al. (2009) recommend mixing highly putrescible OFMSW with municipal grass waste (MGW) to improve process stability, avoid inhibitions and increase methane yields (Schievano et al., 2009). Additionally, OFMSW samples containing cooked and uncooked meat always presented lower methane yields.

Different pretreatment techniques to improve hydrolysis rate in anaerobic digestion have been applied (Panigrahi and Dubey, 2019). Thermal and mechanical pretreatments have been applied at full scales. However, their high demands in energy hinder their benefits (Brémond et al., 2018). Chemical pretreatments are limited at lab scales due to their costs and environmental impact. Lately, there has been an increasing interest in combining pretreatments to reduce the disadvantages of applying single pretreatment techniques in terms of energy use. Wang et al. (2022) studied the effect of co-hydrothermal pretreatment coupled with deep dewatering in CSTR and anaerobic sequencing batch reactors (ASBR) at laboratory scales. VS removal efficiencies increased by 6% and operating costs decreased by 14.9 USD/metric ton of feedstock when ASBR were used (Wang et al., 2022). Moreover, Dutta et al. (2022) implemented a pretreatment technique Advanced Wet Oxidation & Steam Explosion process (AWOEx) to improve thermophilic AD of sewage sludge at lab-scales. Results were promising obtaining a methane yield of 92% in the reactors (Dutta et al., 2022). Lastly, Zheng et al (2023) combined ultrasound and chemical pretreatment on AD of waste activated sludge at laboratory scales, demonstrating that the combination of pretreatments was more effective than a single pretreatment (174.44 mL/g of VS) (Zheng et al., 2023).

Biological pretreatments are gaining interest over time, increasing its scientific production on a 15% ratio from 2011, especially due to their lower energy demand and consumption of chemicals (Brémond et al., 2018). Biological pretreatments imply the use of bacteria, fungi, or enzymes. However, fungal pretreatment studies involving food wastes or OFMSW has not been reported yet (Brémond et al., 2018). Biological pretreatments have been applied at lab scales and some of them at pilot-scales. However, a few studies have been carried out to evaluate the effect of a biological treatment in dry AD or ACoD of the OFMSW. Otto Wagner et al. (2013) used the fungi *Trichoderma viride* cultures to pretreat organic wastes, increasing methane and biogas productions and a better nutrient availability for anaerobic microorganisms (Wagner et al., 2013). Fdez.-Güelfo et al. (2011) evaluated the addition of mature compost to OFMSW to enhance organic matter solubilization. Lab scale thermophilic experiments showed an increase of 60% and 73% on biogas and methane production respectively. Moreover, fungal pretreatment has been explored at lab and pilot scales for substrates different from the OFMSW (Fdez.-Güelfo et al., 2011). Mustafa et al. (2016)

studied fungal pretreatment of rice straw with *P.ostreatus* and *Trichoderma reesei* prior to dry AD. Different moisture contents: 65%, 75% and 85% and pretreatment times: 10, 20 and 30 days were tested. Pretreatment with *P.ostreatus* and *T. reseei* during 20 days of incubation and a moisture content of 75% yielded the best methane volumes (263 and 214 L/kg VS), with an increase of 120% and 78.3% when compared to untreated rice straw (Mustafa et al., 2016).

Rouches et al. (2019) used the WRF *Polyporus brumalis* to pretreat wheat straw in a leach bed reactor. First, the effect of S/I ratio was explored. Then, fungal pretreatment was performed under batch condition at a pilot scale reactor. The authors found that increasing S/I resulted on a higher methane productivity but also raised the risk of failure due to VFA accumulation. They recommended S/I of 1.2 and 3.6 (VS basis). During pilot scale experiments, fungal pretreatment reduced the risk of acidification in the start-up phase-However, a slightly lower methane production was found (161 versus 171 mL/g TS) due to mass losses in the reactors (Rouches et al., 2019). In a different study, the fungus *Trichoderma longibrachiatum* was explored for the pretreatment of rice husk prior to dry AD. The authors suggest that the resulting methane yield (483.1 NmL/g VS added) was higher than the controls, improving the substrate digestibility in high solids loading and improving kinetic parameters. As a result, fungal pretreatment could be an effective low-cost pretreatment for rice husk (Zanellati et al., 2021). Finally, Basinas et al. (2022) evaluated the effect of using *P.ostreatus*, *Dichomitus squalens*, *Trametes versicolor* and *Irpex lacteus* to promote biogas generation from corn silage. *P. ostreatus* and *D. squalens* increase methane generation. However, *T. versicolor* and *I. lacteus* presented a negative effect (Basinas et al., 2022).

Previous research in ACoD allowed to identify an opportunity to explore different strategies to improve methane and biogas yields during dry processes. First, ACoD with dry materials such as MGW would be beneficial for Sabana Centro since it represents around 13% of total MSW and it and has no significant commercial uses or industrial relevance (Danial et al.,

2020) and it is currently being sent to compost in a few municipalities, and the other ones are sending this fraction to landfills. Additionally, there are only a small number of studies exploring the use of MGW as a co-substrate during dry ACoD with OFMSW. Furthermore, the use of fungal pretreatment to enhance methane production from OFMSW is another opportunity due to the lower costs and environmental impact of biological pretreatments. During the present study both strategies were be evaluated at lab-scale, results are presented in chapter 3. Additionally, the process that produced the best methane yields was tested at different pilot-scales and used as baseline to design a full-scale proposal for Sabana Centro, Colombia using a participatory design approach (Chapter 4).

1.4 Justification

Progress in the way power is generated and supplied in society is needed to achieve the transition towards a sustainable world. This requires a radical re-organization in the structure of current energy systems, including the use of new energy sources, technologies for their transformation, and innovative systems for power distribution. A sustainable society entails new ways to harness, transform and use biomass resources. In this context, modern bioenergy systems could play a catalytic role. With this background, the United Nations General Assembly formally adopted the 2030 Agenda for Sustainable Development, along with a set of 17 SGDs and 169 associated targets (Munasinghe, 2017).

Colombia is determined to contribute to this effort and has established specific priorities in relation to the SDGs. In terms of SDG 7, the country issued in 2014, the Law 1715 to promote renewable energy sources for full energy access. By 2019, Colombia had already met and exceeded the renewable electricity generation target set for 2030 in 86.7%, which was 73.3% by 2030 (Departamento Nacional de Planeación, 2019). Thus, there is already a national legal framework covering renewable energy in Colombia. Regarding SDG 12, Colombia has the goal to recycle 17.9% of solid residues by 2030. However, the country is still far behind meeting the goal and recycling rate was still 15% by 2020 (Departamento Nacional de Planeación, 2019). In the country, the development of biomass energy systems has been slow, and authorities have not managed to realize the bioenergy potential at hand, particularly in rural settlements affected by a conflict that lasted more than 50 years.

Sabana Centro is a Colombian province founded in 1998 located in the Department of Cundinamarca. It is formed by eleven municipalities: Cajicá, Chía, Cogua, Cota, Gachancipá, Nemocón, Sopó, Tabio, Tenjo, Tocancipá and Zipaquirá. ASOCENTRO is an institution created in 1990 with the aim of encouraging the collaboration among the eleven municipalities of Sabana Centro to find resources for public services and development of projects. The province of Sabana Centro is a region that plays an essential role in the development and growth of Bogotá (the capital of Colombia). Correspondingly, national authorities support the development of infrastructure, housing, education, and health projects (Pineda et al., 2015). In Sabana Centro, there have been a few initiatives to treat OFMSW. Sabana Centro generates around 127,258 tons of MSW per year and treat 4,288 tons per year (around 3,4% of total MSW). The municipality of Cajicá is the leader in recycling and treating the organic fraction of waste. 2,989 tons of waste per year are composted, this represents a recycling rate of 17% for Cajicá and 70% of total waste treated in Sabana Centro. This success is due to a transition of more than 15 years to source separation policies to promote recycling and treating of waste. Cajicá is an example for the remaining ten municipalities of Sabana Centro. In fact, Chía and Zipaquirá are implementing source separation policies with a specific organic waste collection route twice a week. These three municipalities are currently sending their OFMSW to private composting facilities, although local authorities have the intention to implement technologies that can generate energy from waste.

AD is the most recommended technology to treat the OFMSW (Panigrahi and Dubey, 2019). It would be a beneficial technology for Sabana Centro since source separation policies are already being implemented. AD has been widely implemented around the world. However, the implementation of dry AD still has technical challenges. Carbon to nitrogen ratio (C/N) and ammonia concentration are considered the most relevant parameters influencing stability and performance. Ammonia produced by biological processes of nitrogenous matters usually accumulates during the process and leads to inhibitory effects and further deterioration of the process (Shi et al., 2017). The development of full-scale OFMSW dry AD plants is still challenging due to its high volatile solid and nitrogen contents, leading to possible severe acidification (Jiang et al., 2022; Wang et al., 2014). As a result, the development of laboratory and pilot-scale experiments evaluating strategies to improve biogas and methane yields are still needed.

In the present study, an assessment of a waste-to-energy process for a small region in Colombia is proposed through the application of a novel approach that combines participatory methodologies to gain deep knowledge about the local context and to engage relevant stakeholders and a technical perspective that evaluates technical feasibility through laboratory and pilot scale experiments. The relevance of the study is an approach that considers a broader analysis of a context to propose a technical design that fits to the specific needs of Sabana Centro. Advantages of this project imply benefits and improvements in inhabitant's quality of life and support of SDGs targets set by the country. Through the development of this project, Sabana Centro will have a clear opportunity to increase the share of renewable energy in the energy matrix by the generation of power, reduce GHG emissions by reducing the use of truck for transporting MSW to landfills, and increase the recycling rate by sending organics to AD facilities instead of landfilling. This project supports SDG 7-Ensure access to affordable, reliable, sustainable, and modern energy for all, SDG 10-Sustainable Cities and Communities, and SDG 12 - Ensure sustainable consumption and production patterns (Munasinghe, 2017).

1.5 Research questions

The overarching questions for this study are:

i) What are the most relevant factors affecting sustainable MSW management in Sabana Centro (Colombia)?

ii) How to improve methane production through dry anaerobic digestion of source separated OFMSW?

iii) How to design a dry anaerobic digestion plant to treat the OFMSW available in Sabana Centro considering the characteristics of the local context?

1.6 Objective

The aim of this thesis was:

To assess a comprehensive municipal waste-to-energy dry anaerobic digestion process for the province of Sabana Centro, Colombia combining technical and participatory approaches

Specific objectives

- To outline recommendations to improve Municipal Solid Waste management in Sabana Centro, Colombia
- To evaluate methane production from Organic Fraction of Municipal Solid Waste at both laboratory and pilot scales
- To design a dry anaerobic digestion plant for Sabana Centro, Colombia considering the local context

References of Chapter 1

Abdallah, M., Arab, M., Shabib, A., El-Sherbiny, R., El-Sheltawy, S., 2020. Characterization and sustainable management strategies of municipal solid waste in Egypt. Clean Technol Environ Policy 22, 1371–1383. https://doi.org/10.1007/s10098-020-01877-0

Acero López, A.E., Ramirez Cajiao, M.C., Peralta Mejia, M., Payán Durán, L.F., Espinosa Díaz, E.E., 2019. Participatory Design and Technologies for Sustainable Development: an Approach from Action Research. Syst Pract Action Res 32, 167–191. https://doi.org/10.1007/s11213-018-9459-6

Aguilar, M.G., Jaramillo, J.F., Ddiba, D., Páez, D.C., Rueda, H., Andersson, K., Dickin, S., 2022. Governance challenges and opportunities for implementing resource recovery from organic waste streams in urban areas of Latin America: insights from Chía, Colombia. Sustain Prod Consum 30, 53–63. https://doi.org/10.1016/j.spc.2021.11.025

Alibardi, L., Cossu, R., 2015. Composition variability of the organic fraction of municipal solid waste and effects on hydrogen and methane production potentials. Waste Management 36, 147–155. https://doi.org/10.1016/j.wasman.2014.11.019

AlQattan, N., Acheampong, M., Jaward, F.M., Ertem, F.C., Vijayakumar, N., Bello, T., 2018. Reviewing the potential of Waste-to-Energy (WTE) technologies for Sustainable Development Goal (SDG) numbers seven and eleven. Renewable Energy Focus. https://doi.org/10.1016/j.ref.2018.09.005

André, L., Pauss, A., Ribeiro, T., 2018. Solid anaerobic digestion : State-of-art , scientific and technological hurdles. Bioresour Technol 247, 1027–1037. https://doi.org/10.1016/j.biortech.2017.09.003

Ara, E., Sartaj, M., Kennedy, K., 2015. Enhanced biogas production by anaerobic co-digestion from a trinary mix substrate over a binary mix substrate. Waste Management and Research 33, 578–587. https://doi.org/10.1177/0734242X15584844

Ariunbaatar, J., Panico, A., Esposito, G., Pirozzi, F., Lens, P.N.L., 2014. Pretreatment methods to enhance anaerobic digestion of organic solid waste. Appl Energy 123, 143–156. https://doi.org/10.1016/j.apenergy.2014.02.035

Barampouti, E.M., Mai, S., Malamis, D., Moustakas, K., Loizidou, M., 2019. Liquid biofuels from the organic fraction of municipal solid waste : A review. Renewable and Sustainable Energy Reviews 110, 298–314. https://doi.org/10.1016/j.rser.2019.04.005

Basinas, P., Rusín, J., Chamrádová, K., Malachová, K., Rybková, Z., Novotný, Č., 2022. Fungal pretreatment parameters for improving methane generation from anaerobic digestion of corn silage. Bioresour Technol 345. https://doi.org/10.1016/j.biortech.2021.126526

Batista, M., Goyannes Gusmão Caiado, R., Gonçalves Quelhas, O.L., Brito Alves Lima, G., Leal Filho, W., Rocha Yparraguirre, I.T., 2021. A framework for sustainable and integrated municipal solid waste management: Barriers and critical factors to developing countries. J Clean Prod 312. https://doi.org/10.1016/j.jclepro.2021.127516

Bertolucci Paes, L.A., Stolte Bezerra, B., Mattos Deus, R., Jugend, D., Gomes Battistelle, R.A., 2019. Organic solid waste management in a circular economy perspective - A systematic review and SWOT analysis. J Clean Prod 239, 118086. https://doi.org/10.1016/j.jclepro.2019.118086

Beschkov, V., 2017. Biogas, Biodiesel and Bioethanol as Multifunctional Renewable Fuels and Raw Materials, in: Frontiers in Bioenergy and Biofuels. InTech. https://doi.org/10.5772/65734

Borowski, S., 2015. Temperature-phased anaerobic digestion of the hydromechanically separated organic fraction of municipal solid waste with sewage sludge. Int Biodeterior Biodegradation 105, 106–113. https://doi.org/10.1016/j.ibiod.2015.08.022

Brémond, U., de Buyer, R., Steyer, J.P., Bernet, N., Carrere, H., 2018. Biological pretreatments of biomass for improving biogas production: an overview from lab scale to full-scale. Renewable and Sustainable Energy Reviews 90, 583–604. https://doi.org/10.1016/j.rser.2018.03.103

Bres, P., Beily, E., Young, B.J., Gasulla, J., Butti, M., Crespo, D., Candal, R., Komilis, D., 2018. Performance of semi-continuous anaerobic co-digestion of poultry manure with fruit and vegetable waste and analysis of digestate quality: A bench scale study. Waste Management 82, 276–284. https://doi.org/10.1016/j.wasman.2018.10.041

Brown, D., Li, Y., 2013. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. Bioresour Technol 127, 275–280. https://doi.org/10.1016/j.biortech.2012.09.081

Calderón Márquez, A.J., Rutkowski, E.W., 2020. Waste management drivers towards a circular economy in the global south – The Colombian case. Waste Management 110, 53–65. https://doi.org/10.1016/j.wasman.2020.05.016

Cetrulo, T.B., Marques, R.C., Cetrulo, N.M., Pinto, F.S., Moreira, R.M., Mendizábal-Cortés, A.D., Malheiros, T.F., 2018. Effectiveness of solid waste policies in developing countries: A case study in Brazil. J Clean Prod 205, 179–187. https://doi.org/10.1016/j.jclepro.2018.09.094

Cremiato, R., Mastellone, M.L., Tagliaferri, C., Zaccariello, L., Lettieri, P., 2018. Environmental impact of municipal solid waste management using Life Cycle Assessment: The effect of anaerobic digestion, materials recovery and secondary fuels production. Renew Energy 124, 180–188. https://doi.org/10.1016/j.renene.2017.06.033

Cuetos, M.J., Gómez, X., Otero, M., Morán, A., 2008. Anaerobic digestion of solid slaughterhouse waste (SHW) at laboratory scale: Influence of co-digestion with the organic fraction of municipal solid waste (OFMSW). Biochem Eng J 40, 99–106. https://doi.org/10.1016/j.bej.2007.11.019

Danial, W.H., Mohd Taib, R., Abu Samah, M.A., Mohd Salim, R., Abdul Majid, Z., 2020. The valorization of municipal grass waste for the extraction of cellulose nanocrystals. RSC Adv 10, 42400–42407. https://doi.org/10.1039/d0ra07972c

Departamento Nacional de Planeación, 2019. Objetivos de Desarrollo Sostenible [WWW Document]. Explore los datos.

Dutta, N., Giduthuri, A.T., Usman Khan, M., Garrison, R., Ahring, B.K., 2022. Improved valorization of sewage sludge in the circular economy by anaerobic digestion: Impact of an innovative pretreatment technology. Waste Management 154, 105–112. https://doi.org/10.1016/j.wasman.2022.09.035

Ebrahimian, F., Denayer, J.F.M., Mohammadi, A., Khoshnevisan, B., Karimi, K., 2022. A critical review on pretreatment and detoxification techniques required for biofuel production from the organic fraction of municipal solid waste. Bioresour Technol 128316. https://doi.org/10.1016/j.biortech.2022.128316

Fan, Y. Van, Lee, C.T., Jaromír, J.K., 2017. The Update of Anaerobic Digestion and the Environment Impact Assessments Research 57, 7–12. https://doi.org/10.3303/CET1757002

Fdez.-Güelfo, L.A., Álvarez-Gallego, C., Sales Márquez, D., Romero García, L.I., 2011. Biological pretreatment applied to industrial organic fraction of municipal solid wastes (OFMSW): Effect on anaerobic digestion. Chemical Engineering Journal 172, 321–325. https://doi.org/10.1016/j.cej.2011.06.010

Ferronato, N., Moresco, L., Guisbert Lizarazu, G.E., Gorritty Portillo, M.A., Conti, F., Torretta, V., 2021. Sensitivity analysis and improvements of the recycling rate in municipal solid waste life cycle assessment: Focus on a Latin American developing context. Waste Management 128, 1–15. https://doi.org/10.1016/j.wasman.2021.04.043

Florio, C., Nastro, R.A., Flagiello, F., Minutillo, M., Pirozzi, D., Pasquale, V., Ausiello, A., Toscano, G., Jannelli, E., Dumontet, S., 2019. Biohydrogen production from solid phase-microbial fuel cell spent substrate: A preliminary study. J Clean Prod 227, 506–511. https://doi.org/10.1016/j.jclepro.2019.03.316

Franceschi, F.F., Vega, L.T., Sanches-Pereira, A., Cherni, J.A., Gómez, M.F., 2022. A combined approach to improve municipal solid waste management in upper-middle-income countries: the case of Sabana Centro, Colombia. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-022-02333-x

Ge, X., Xu, F., Li, Y., 2016. Solid-state anaerobic digestion of lignocellulosic biomass: Recent progress and perspectives. Bioresour Technol 205, 239–249. https://doi.org/10.1016/j.biortech.2016.01.050

Hartmann, H., Ahring, B.K., 2005. Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure. Water Res 39, 1543–1552. https://doi.org/10.1016/j.watres.2005.02.001

Holland Circular Hotspot, 2021. Waste Management Country Report: Colombia.

Jiang, H., Wang, S., Li, B., Feng, L., Zhai, L., Zhou, H., Li, Y., Pan, J., 2022. Anaerobic digestion of organic fraction of municipal solid waste using a novel two-stage solid-liquid system. J Clean Prod 370. https://doi.org/10.1016/j.jclepro.2022.133521

Jiang, Y., Dennehy, C., Lawlor, P.G., Hu, Z., McCabe, M., Cormican, P., Zhan, X., Gardiner, G.E., 2018. Inhibition of volatile fatty acids on methane production kinetics during dry co-digestion of food waste and pig manure. Waste Management 79, 302–311. https://doi.org/10.1016/j.wasman.2018.07.049

Jiang, Y., McAdam, E., Zhang, Y., Heaven, S., Banks, C., Longhurst, P., 2019. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. Journal of Water Process Engineering. https://doi.org/10.1016/j.jwpe.2019.100899

Jin, E., Mendis, G.P., Sutherland, J.W., 2019. Integrated sustainability assessment for a bioenergy system: A system dynamics model of switchgrass for cellulosic ethanol production in the U.S. midwest. J Clean Prod 234, 503–520. https://doi.org/10.1016/j.jclepro.2019.06.205

Khan, A.H., López-Maldonado, E.A., Alam, S.S., Khan, N.A., López, J.R.L., Herrera, P.F.M., Abutaleb, A., Ahmed, S., Singh, L., 2022. Municipal solid waste generation and the current state of waste-to-energy potential: State of art review. Energy Convers Manag. https://doi.org/10.1016/j.enconman.2022.115905

Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018. Circular economy as an essentially contested concept. J Clean Prod 175, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111

Kourkoumpas, D., Karellas, S., Kouloumoundras, S., 2015. Comparison of Waste-to-Energy Processes by Means of Life Cycle Analysis Principles regarding the Global Warming Potential Impact : Applied Case Studies in Greece , France and Germany. Waste Biomas Valorisation. https://doi.org/10.1007/s12649-015-9367-2

Krishna, D., Kalamdhad, A.S., 2014. Pre-treatment and anaerobic digestion of food waste for high rate methane production - A review. J Environ Chem Eng 2, 1821–1830. https://doi.org/10.1016/j.jece.2014.07.024

Kunze, O., Wulfhorst, G., Minner, S., 2016. Applying Systems Thinking to City Logistics: A Qualitative (and Quantitative) Approach to Model Interdependencies of Decisions by various Stakeholders and their Impact on City Logistics, in: Transportation Research Procedia. Elsevier B.V., pp. 692–706. https://doi.org/10.1016/j.trpro.2016.02.022

Li, Y., Chen, Y., Wu, J., 2019. Enhancement of methane production in anaerobic digestion process: A review. Appl Energy 240, 120–137. https://doi.org/10.1016/j.apenergy.2019.01.243

Linss, V., Fried, A., 2010. The ADVIAN® classification - A new classification approach for the rating of impact factors. Technol Forecast Soc Change 77, 110–119. https://doi.org/10.1016/j.techfore.2009.05.002

Lukajtis, R., Holowacz, I., Kucharska, K., Glinka, M., Rybarczyk, P., Przyjazny, A., Kaminski, M., 2018. Hydrogen production from biomass using dark fermentation 91, 665–694. https://doi.org/10.1016/j.rser.2018.04.043

Margallo, M., Ziegler-Rodriguez, K., Vázquez-Rowe, I., Aldaco, R., Irabien, Á., Kahhat, R., 2019. Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A review for policy support. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2019.06.393

Matsakas, L., Gao, Q., Jansson, S., Rova, U., Christakopoulos, P., 2017. Green conversion of municipal solid wastes into fuels and chemicals 26, 69–83. https://doi.org/10.1016/j.ejbt.2017.01.004

Mayer, F., Bhandari, R., Gäth, S., 2019. Science of the Total Environment Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies 672, 708–721. https://doi.org/10.1016/j.scitotenv.2019.03.449

Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S.J., Ulgiati, S., 2018. Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. Environments - MDPI 5, 1–19. https://doi.org/10.3390/environments5020024

Mirmohamadsadeghi, S., Karimi, K., Tabatabaei, M., 2019. Bioresource Technology Reports Biogas production from food wastes : A review on recent developments and future perspectives 7. https://doi.org/10.1016/j.biteb.2019.100202

Moestedt, J., Nordell, E., Shakeri Yekta, S., Lundgren, J., Martí, M., Sundberg, C., Ejlertsson, J., Svensson, B.H., Björn, A., 2016. Effects of trace element addition on process stability during anaerobic co-digestion of OFMSW and slaughterhouse waste. Waste Management 47, 11–20. https://doi.org/10.1016/j.wasman.2015.03.007

Moreno, L.A., Defterli, O., Fügenschuh, A., Weber, G.-W., 2014. Vester's Sensitivity Model for Genetic Networks with Time-Discrete Dynamics.

Munasinghe, M., 2017. Sustainable Development: Basic Concepts and Application to Energy. Encyclopedia of Energy 5, 0–20. https://doi.org/10.1016/B0-12-176480-X/00441-1

Mustafa, A.M., Poulsen, T.G., Sheng, K., 2016. Fungal pretreatment of rice straw with Pleurotus ostreatus and Trichoderma reesei to enhance methane production under solid-state anaerobic digestion. Appl Energy 180, 661–671. https://doi.org/10.1016/j.apenergy.2016.07.135

Ning, T., Chong, D., Jia, M., Wang, J., Yan, J., 2015. Experimental investigation on the performance of wet cooling towers with defects in power plants. Appl Therm Eng 78, 228–235. https://doi.org/10.1016/j.applthermaleng.2014.12.032

Panigrahi, S., Dubey, B.K., 2019. A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew Energy 143, 779–797. https://doi.org/10.1016/j.renene.2019.05.040

Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N., Ujang, Z. Bin, 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J Clean Prod 76, 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020

Pezzolla, D., Di Maria, F., Zadra, C., Massaccesi, L., Sordi, A., Gigliotti, G., 2017. Optimization of solid-state anaerobic digestion through the percolate recirculation. Biomass Bioenergy 96, 112–118. https://doi.org/10.1016/j.biombioe.2016.11.012

Pineda, N.M., Camelo, J.C., Bejarano, A.M., Castro, L.A., Vengoechea, J.R., Ortíz, J.G., 2015. Sabana Centro Cómo Vamos Informe de calidad de vida Sabana Centro Cómo Vamos Línea base 2014-2015 180.

Qazi, W.A., Abushammala, M.F.M., 2018. Multi-criteria decision analysis of waste- to-energy technologies for municipal solid waste management in Sultanate of Oman. https://doi.org/10.1177/0734242X18777800

Rouches, E., Escudié, R., Latrille, E., Carrère, H., 2019. Solid-state anaerobic digestion of wheat straw: Impact of S/I ratio and pilot-scale fungal pretreatment. Waste Management 85, 464–476. https://doi.org/10.1016/j.wasman.2019.01.006

Rouches, E., Herpoël-Gimbert, I., Steyer, J.P., Carrere, H., 2016. Improvement of anaerobic degradation by white-rot fungi pretreatment of lignocellulosic biomass: A review. Renewable and Sustainable Energy Reviews 59, 179–198. https://doi.org/10.1016/j.rser.2015.12.317

Sanders, E., Jan Stappers, P., 2008. Co-creation and the new landscapes of design. Codesign 799–809. https://doi.org/10.1080/15710880701875068

Sawatdeenarunat, C., Surendra, K.C., Takara, D., Oechsner, H., Kumar, S.K., 2015. Bioresource Technology Anaerobic digestion of lignocellulosic biomass : Challenges and opportunities. Bioresour Technol 178, 178–186. https://doi.org/10.1016/j.biortech.2014.09.103

Schievano, A., D'Imporzano, G., Malagutti, L., Fragali, E., Ruboni, G., Adani, F., 2010. Evaluating inhibition conditions in high-solids anaerobic digestion of organic fraction of municipal solid waste. Bioresour Technol 101, 5728–5732. https://doi.org/10.1016/j.biortech.2010.02.032

Schievano, A., Scaglia, B., D'Imporzano, G., Malagutti, L., Gozzi, A., Adani, F., 2009. Prediction of biogas potentials using quick laboratory analyses: Upgrading previous models for application to heterogeneous organic matrices. Bioresour Technol 100, 5777–5782. https://doi.org/10.1016/j.biortech.2009.05.075

Shi, X., Lin, J., Zuo, J., Li, P., Li, X., Guo, X., 2017. Effects of free ammonia on volatile fatty acid accumulation and process performance in the anaerobic digestion of two typical bio-wastes. J Environ Sci (China) 55, 49–57. https://doi.org/10.1016/j.jes.2016.07.006

Silva Martinez, D. R. (2021). Dry anaerobic digestion treatment potential for the organic fraction of municipal solid waste in Brazil and Mexico.

Silva-Martínez, R.D., Sanches-Pereira, A., Ortiz, W., Gómez Galindo, M.F., Coelho, S.T., 2020. The state-of-the-art of organic waste to energy in Latin America and the Caribbean: Challenges and opportunities. Renew Energy 156, 509–525. https://doi.org/10.1016/j.renene.2020.04.056

Silvestre, G., Bonmatí, A., Fernández, B., 2015. Optimisation of sewage sludge anaerobic digestion through co-digestion with OFMSW: Effect of collection system and particle size. Waste Management 43, 137–143. https://doi.org/10.1016/j.wasman.2015.06.029

Tan, S.T., Ho, W.S., Hashim, H., Lee, C.T., Taib, M.R., Ho, C.S., 2015a. Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia. Energy Convers Manag 102, 111–120. https://doi.org/10.1016/j.enconman.2015.02.010

Tan, S.T., Ho, W.S., Hashim, H., Lee, C.T., Taib, M.R., Ho, C.S., 2015b. Energy , economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in 102, 111–120. https://doi.org/10.1016/j.enconman.2015.02.010

The World Bank, 2021. World Bank Country and Lending Groups [WWW Document]. Data (Basel).

Tozlu, A., Özahi, E., 2016. Waste to energy technologies for municipal solid waste management in Gaziantep 54, 809–815. https://doi.org/10.1016/j.rser.2015.10.097

Tsai, F.M., Bui, T.D., Tseng, M.L., Lim, M.K., Hu, J., 2020. Municipal solid waste management in a circular economy: A data-driven bibliometric analysis. J Clean Prod 275. https://doi.org/10.1016/j.jclepro.2020.124132

Tuor, U., Winterhalter, K., Fiechter, A., 1995. Enzymes of white-rot fungi involved in lignin degradation and ecological determinants for wood decay, Journal of Biotechnology.

Tyagi, V.K., Fdez-Güelfo, L.A., Zhou, Y., Álvarez-Gallego, C.J., Garcia, L.I.R., Ng, W.J., 2018. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2018.05.051

UAESP, 2011. Caracterización de los residuos sólidos de establecimientos comerciales, pequeños productores, generados en la ciudad de Bogotá D.C. 56.

Van den Burg, S., Stuiver, M., Norrman, J., Garção, R., Söderqvist, T., Röckmann, C., Schouten, J.J., Petersen, O., García, R.G., Diaz-Simal, P., Bel, M. de, Aja, L.M., Zagonari, F., Zanuttigh, B., Sarmiento, J., Giannouli, A., Koundouri, P., 2016. Participatory design of multi-use platforms at sea. Sustainability (Switzerland) 8, 1–17. https://doi.org/10.3390/su8020127

Vester, F., 2007. The Art of Interconnected Thinking: Tools and Concepts for a New Approach to Tackling Complexity. Munich.

Vinti, G., Bauza, V., Clasen, T., Medlicott, K., Tudor, T., Zurbrügg, C., Vaccari, M., 2021. Municipal solid waste management and adverse health outcomes: A systematic review. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph18084331

Wagner, A.O., Schwarzenauer, T., Illmer, P., 2013. Improvement of methane generation capacity by aerobic pre-treatment of organic waste with a cellulolytic Trichoderma viride culture. J Environ Manage 129, 357–360. https://doi.org/10.1016/j.jenvman.2013.07.030

Wang, L., Shen, F., Yuan, H., Zou, D., Liu, Y., Zhu, B., Li, X., 2014. Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies. Waste Management 34, 2627–2633. https://doi.org/10.1016/j.wasman.2014.08.005

Wang, Yidi, Li, W., Wang, Yongkang, Turap, Y., Wang, Z., Zhang, Z., Xia, Z., Wang, W., 2022. Anaerobic co-digestion of food waste and sewage sludge in anaerobic sequencing batch reactors with application of co-hydrothermal pretreatment of sewage sludge and biogas residue. Bioresour Technol 364. https://doi.org/10.1016/j.biortech.2022.128006

Wesselink, A., Paavola, J., Fritsch, O., Renn, O., 2011. Rationales for public participation in environmental policy and governance: Practitioners' perspectives. Environ Plan A 43, 2688–2704. https://doi.org/10.1068/a44161

Wolf, C., Persson, F., Jelse, K., 2012. A logistic analysis with the Sensitivity Model Prof. Vester.

World Bank Group, 2018. What a Waste 2.0 Introduction -"Snapshot of Solid Waste Management to 2050." Overview booklet. Urban Development Series 1–38.

Yap, H.Y., Nixon, J.D., 2015. A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK. https://doi.org/10.1016/j.wasman.2015.08.002

Zanellati, A., Spina, F., Poli, A., Rollé, L., Varese, G.C., Dinuccio, E., 2021. Fungal pretreatment of non-sterile maize silage and solid digestate with a Cephalotrichum stemonitis strain selected from agricultural biogas plants to enhance anaerobic digestion. Biomass Bioenergy 144. https://doi.org/10.1016/j.biombioe.2020.105934

Zhang, C., Xiao, G., Peng, L., Su, H., Tan, T., 2013. The anaerobic co-digestion of food waste and cattle manure. Bioresour Technol 129, 170–176. https://doi.org/10.1016/j.biortech.2012.10.138

Zheng, K., Wang, Y., Wang, X., Zhu, T., Chen, X., Zhao, Y., Sun, P., Tong, Y., Liu, Y., 2023. Enhanced methane production from anaerobic digestion of waste activated sludge by combining ultrasound with potassium permanganate pretreatment. Science of the Total Environment 857. https://doi.org/10.1016/j.scitotenv.2022.159331

Chapter 2

A combined approach to improve municipal solid waste management in upper-middle income countries: the case of Sabana Centro, Colombia

Before evaluating waste-to-energy technologies from a technical perspective to propose a suitable alternative for Sabana Centro, it was relevant for the authors to study local context to gain knowledge about the factors that hinder the implementation of these technologies in upper-middle income countries, especially in Colombia. Accordingly, this thesis started with the application of a novel combined approach using impact analysis and participatory workshops to obtain deep knowledge about local dynamics and to formulate recommendations to support the implementation of these technologies. Relevant stakeholders' perspectives on the context were included through participatory workshops in which the impact analysis was carried out. This study was part of a project funded by the Ministry of Science, Innovation and Technology of Colombia (Minciencias), and developed together with national entities such as the Botanical Garden of Bogota (JBB[2]) and ASOCENTRO[3] (an organization in charge of evaluation and development of projects in Sabana Centro). The following article was published by the journal Clean Technologies and Environmental Policy, and the proposed methodology can be useful to understand MSW systems in upper-middle income countries.

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[2] In Spanish, the Botanical Garden of Bogotá

[3] In Spanish, Asociación de Municipios de Sabana Centro

A combined approach to improve municipal solid waste management in upper-middle income countries: the case of Sabana Centro, Colombia[4]

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Abstract

In developing countries, the lack of specific knowledge of the local context and complex interactions among variables influence effective solid waste management. As a result, the formulation of effective strategies to improve waste management is still a challenge. This study draws on the principle that an adequate formulation of recommendations can be achieved through deep knowledge of the context of implementation, specific for each country. This research designs and applies a novel impact analysis combined with participatory workshops to formulate recommendations to enhance municipal solid waste management. The approach includes four components: i) a systematic literature review to identify the factors that affect municipal solid waste management in upper-middle income countries; ii) participatory workshops to collect information directly from relevant stakeholders; iii) an impact matrix to systematize valuable information obtained from i) and ii), and iv) an impact analysis to classify the information obtained and develop recommendations to improve municipal solid waste management. The combined approach can be applied to upper-middle income countries. A case study was applied in Sabana Centro, a region in Colombia composed by 11 municipalities, to exemplify the use of this approach. Key recommendations to improve sustainable waste management in Sabana Centro emerged from this study, i.e., creating multiple funding schemes, the need for new Public-Private Partnerships, the promotion of waste treatment technologies, the encouragement of public involvement in source separation activities, and the alignment of local waste management plans inside Sabana Centro and with the national waste management policy.

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[4] Version published by Clean Technologies and Environmental Policy

Keywords: municipal solid waste, upper-middle income countries, impact analysis, participatory workshops, waste management.

2.1 Introduction

Municipal Solid Waste (MSW) is a consequence of human daily life, and its proper management is a starting point for a healthier urban society (Inglezakis et al., 2018). Inappropriate management of MSW has been associated with hazardous chemicals release, deforestation, affectations to human health, land degradation, among other environmental, social, and economic impacts (Ferronato and Torretta, 2019). According to the World Bank, the solid waste generated from urban areas globally is expected to increase from 3.5 million tons per day to 6.1 million tons per day by 2025 (Makarichi et al., 2018). This increasing pace has exceeded the handling capacity of municipalities, especially in developing countries (Anwar et al., 2018) where solid waste management is inefficient due to a lack of proper administrative, infrastructure and adequate resource utilization (Tsai et al., 2020). Nowadays, waste management not only aims to reduce volumes of waste but to incorporate concepts of waste prevention, recycling, and waste-to-energy (WtE) (Abushammala and Qazi, 2021). Scientists and policymakers are dedicating efforts to find more sustainable means of disposal and to develop technologies that utilize MSW as a resource in energy production.

Colombia is one of the most important economies in South America. An accelerated economic growth has promoted an increase in consumption levels and the generation of more waste. At the same time, increased consumption has led to higher energy demand. However, few efforts are in place to take full advantage of the energy content of MSW (Superintendencia de Servicios Públicos Domiciliarios, 2019). Colombia produces an average of 0.63 kg of municipal solid waste per person per day, waste production is growing every year, and the recycling rate is only 17% of total waste. Even though few municipalities recycle inorganic materials such as plastics or metals, there is no generalized intention to prevent waste generation, reuse is not encouraged, and the use of urban waste for energy generation is not implemented yet. It is important to keep in mind that effective waste management is expensive, often comprising a large portion of the very restricted municipal budgets.

The formulation of MSW management strategies require a deep knowledge of regulations, the selection of an appropriate conversion technology, and the understanding of the challenges inherent with new technology adoption (Coventry et al., 2016). Several studies for developing countries have highlighted the relevance of understanding local factors to guide the decision-making processes in the assertive development of policies and strategies to support sustainable solid waste management. Batista et al. (2021) proposed a framework for sustainable integrated MSW management in developing countries considering the barriers and critical factors to achieve it (Batista et al., 2021a). Similarly, Qing et al. (2010) analyzed the problems and challenges of MSW management in China and several recommendations were made to improve the system (Qing et al., 2010). Circular economy in waste management has been also promoted by the identification of critical factors (Salmenperä et al., 2021) and a combined systematic review and SWOT analysis (Bertolucci Paes et al., 2019).

Due to the high complexity in these systems, systemic approaches that consider the specific location and the dynamics of the technical and institutional structures in particular contexts must be developed and tested. Knowledge of the relationships and interactions between different factors is necessary to understand the behavior of the system and support the decision-making process to adopt the adequate transformations. Impact analysis is a well-recognized method to scrutinize different types of systems. Its application can help to identify the variables that play a significant role in the evolution of the system (Guertler and Spinler, 2015). Vester and Hesler (2007) proposed an impact matrix initially for forecasting purposes (Vester, 2007). The matrix has been used in different contexts to study the interrelationships among the system variables (Krieger et al., 2017). Later, Linss and Fried (2009) developed the Advanced Impact Analysis (ADVIAN®) classification method based on the impact analysis to study indirect relationships among variables and calculate supplementary indices for a better understanding of the system (Guertler and Spinler, 2015; Linss and Fried, 2009). Participatory approaches have been developed for business and modelling. However, few approaches have been applied in the waste management field (Martins et al., 2018).

The performance of waste management systems is influenced by financial, environmental, social, and political aspects (Mmereki et al., 2016). The relevance of each aspect and the interactions among them depend on specific dynamics of the local context, that differ among countries. As a result, methods that can help on the decision-making processes must consider the local context and its dynamics. While there have been studies to identify barriers, challenges, and opportunities to sustainable waste management in developing countries, there is no study that combines impact analysis and participatory approaches to enhance MSW management in developing countries. To fill this gap, this paper aims to propose an innovative approach that combines an impact analysis with participatory workshops to develop recommendations to improve MSW management in upper-middle income countries. The combined approach considered participatory workshops as part of the impact analysis to gain understanding of the context. This will translate in positive results in MSW management through the development of recommendations based in the specific behavior of the local context. This approach was applied to Sabana Centro, Colombia as a case study with the idea of providing an example of its application, which can be reproduced in upper-middle income countries.

2.2 Methodological approach

This research proposes the combination of two methods to formulate recommendations to improve MSW management in upper-middle income countries. The World Bank classifies the world’s economies into four income groups based on the Gross National Income (GNI) per capita: low, lower-middle, upper-middle, and high-income countries. Colombia is classified as an upper-middle income country (GNI 4,096 -12,695 USD) (The World Bank, 2021a). The approach is presented in Figure 2.1. To illustrate the application of the approach, a case study was performed for Sabana Centro province in Colombia.

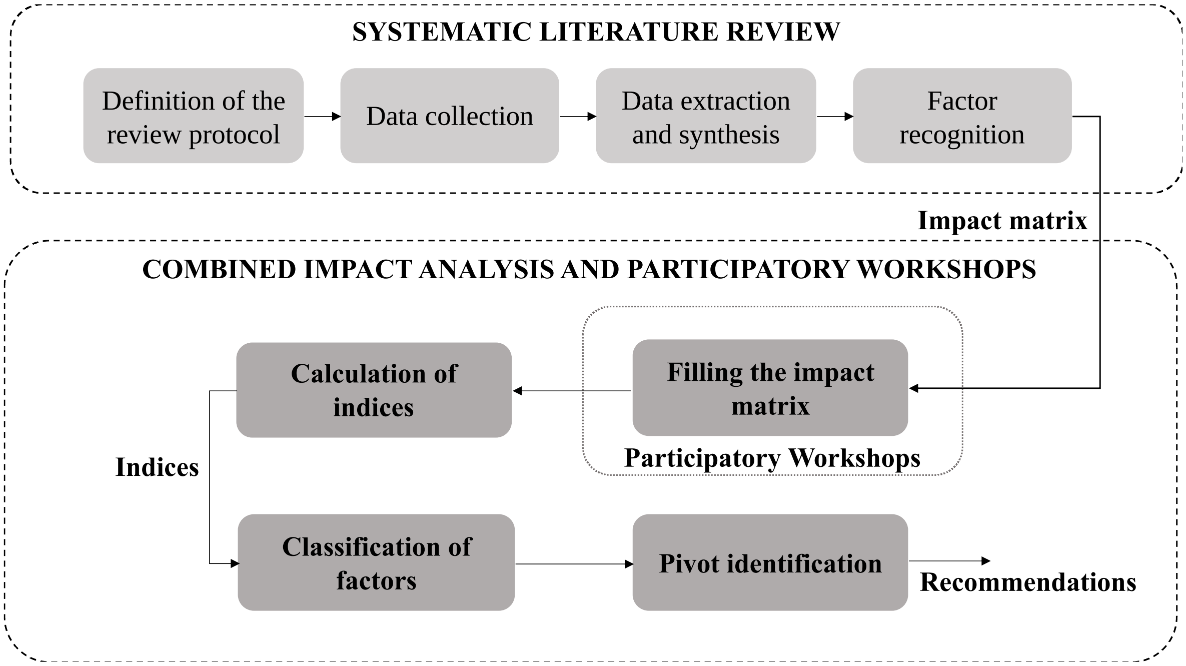

Figure 2. 1. Methodological approach for municipal solid waste management assessment.

2.2.1 Systematic Literature Review: impact factor recognition

A systematic literature review was performed to build the impact matrix used for the combined analysis. This impact matrix can be applied in upper-middle income countries and is used as starting point to perform the combined analysis proposed in the present study. The review protocol consisted of a primary study research using a search string composed by the terms representing the population: solid waste management, municipal solid waste, and indicators: barriers, challenges, recommendations, strategies. The search string captured 23,846 publications. Then, inclusion and exclusion criteria were applied. Inclusion criteria considered the following databases: Science Direct, Latindex, Scielo, Google Scholar, and local publications and regulations considering a timeframe from 2010 to 2020, documents in English and Spanish, only studies applied in upper-middle income countries and developing countries in general, and journals classified as Q1/Q2. Exclusion criteria contemplated: short length publications with less than 5 pages, workshop articles or conference papers, tech reports, and articles not directly related to waste management. After the implementation of inclusion and exclusion criteria, only 49 publications were left for detailed screening. After performing a quality assessment, 32 studies were selected for data extraction and synthesis. Finally, the backward snowball technique was applied (Wohlin, 2014), and 9 more studies were included. A total of 41 publications were chosen for data synthesis and extraction of data. For this study, impact factors (IF) are a set of variables that describe MSW management systems. Vester (2007) recommends a range between 20-40 for the Ifs (Vester, 2007). However, the number of IFs selected for the present study were purposely reduced, because filling the impact matrix for more than 15 factors would have been a very long process during participatory workshops. As a result, some variables were combined. These IFs were classified as financial, social, regulatory, institutional, and technical. Based on the impact factors, an impact matrix that describe MSW management in upper-middle income countries was built.

2.2.2 The combined impact analysis and participatory workshops

2.2.2.1 Filling the impact matrix: participatory workshops

The combined approach proposed in the present study considers participatory workshops. Participatory workshops were applied since they bring a group of people together with the aim of seeking opinions, knowledge with a creative and collaborative approach (Jisc, 2012). In our approach, the workshops provided the basis to build the impact matrix. The impact matrix is the starting point of the impact analysis. The rows of the impact matrix contain the impact strengths of a considered IF on the system of IFs arranged in the columns, the main diagonal is filled with 0 because there is no impact from a factor on itself (Linss and Fried, 2009). The active sum (AS) is the sum of the values in the rows and the passive sum (PS) is the sum of the values in the columns. AS indicates how strongly a factor is affecting the system and the PS represents the sensitivity of a factor to changes within the system (Schianetz and Kavanagh, 2008).

The aim of the workshops was to gather insights to fill the impact matrix as the first step of the impact analysis. Through the workshops, knowledge of the interactions among the IF is gained through different points of view of the stakeholders. In each workshop, participants rated the impact of one factor on the others, using a template of the impact matrix Figure 2.2. Facilitators of the workshops were trained in the moderation of group discussion and the process of building the matrix. The question which was addressed to the participants and used for to rate the impact was: “if variable A changes, how will variable B change in the Colombian waste management system?”. Influence was categorized by the following system: (0) no influence “change of factor A causes no/very weak change of B or change of factor A causes change of B after a significant time delay”, (1) weak influence “strong change of factor A causes small change of B”, (2) moderate influence “change of factor A results in similar change of B” and (3) strong influence “small change of indicator A causes strong change of B”. Results from each workshop were computed into a Microsoft Excel application specifically designed for the analysis. To the authors’ knowledge, there are no other studies with the aim of understanding complex waste management systems in upper-middle income countries using participatory workshops.

During the present study, the case of small cities (around 60,000 inhabitants) in upper-middle income countries was evaluated by performing participatory workshops in Sabana Centro province in Colombia. Sabana Centro is a Colombian province founded in 1998 located in the Department of Cundinamarca. It is formed by eleven municipalities: Cajicá, Chía, Cogua, Cota, Gachancipá, Nemocón, Sopó, Tabio, Tenjo, Tocancipá and Zipaquirá. The province of Sabana Centro is a region that plays an essential role in the development and growth of Bogotá (the capital of Colombia) and the Department of Cundinamarca. As a result, Sabana Centro is suitable for the development of infrastructure, housing, education, and health projects (Rojas et al., 2020). Sabana Centro generates around 127,258 tons of Municipal Solid Waste (MSW) per year and treats 4,288 tons per year (around 3.4% of total MSW). The municipality of Cajicá is the national leader in recycling and treating the putrescible organic fraction of municipal solid waste. 2,989 tons of waste per year are composted, this represents a recycling rate of 17% for Cajicá and 70% of total waste treated in Sabana Centro. This success is due to a transition of more than 15 years to source separation policies to promote recycling and treating of waste. Cajicá is an example for the remaining ten municipalities of Sabana Centro.

As part of the impact analysis, three participatory workshops were performed with participation of stakeholders in Cajicá, Chía and Zipaquirá, the biggest municipalities in Sabana Centro, representing about 64% of its population. Lastly, a final workshop was applied with a team of researchers. Selection of the cities for the application of the workshops was made considering the following aspects: Cajicá is a small city near Bogotá and is the leader of the country in recycling and treating waste. Chía and Zipaquirá, that are also implementing source separation policies and treating the organic fraction of MSW. Zipaquirá, Chia and Cajicá represent more than 60% of total urban area of Sabana Centro and generate more than 65% of total waste generation in Sabana Centro (Rojas et al., 2020). According to Sebastian et al. (2020) relevant stakeholders in the waste management are waste generators, national and local governmental bodies, non-governmental organizations, and private organizations (Sebastian et al., 2020). The participants of each workshop were: one participant of environmental entities, the director of the public service company, the director of local waste collector associations, the local solid waste management plan (PGIRS[5]) coordinator, and a representative of the community. The last workshop was developed with support from a team of five researchers, providing insights from an academic perspective.

2.2.2.2 Calculation of indices

During the present study, relevant indices were calculated to classify the factors Table 2.1. The idea is to identify the factors that can be suitable for immediate changes, causing positive effects on the system and formulate recommendations to improve the whole MSW system. This will help local authorities in the decision-making process. Direct active and passive sums

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[5] In Spanish, Plan Integral de Gestión de Residuos Sólidos

were calculated according to Vester (Vester, 2007). Then, supplementary indices were calculated by a matrix multiplication method as reported by the ADVIAN® classification method (Linss and Fried, 2010). Through the application of the matrix multiplication method, indirect relationships among factors can be contemplated. These indices were calculated in a Microsoft Excel application specially developed for the study.

Table 2.1.Indices calculated as part of the proposed approach.

Index	Description	Method
Direct active sum d(AS)	Indicates how strongly a factor is affecting the system. Sum of the values in the rows.	The impact matrix (Vester, 2007)
Direct passive sum d(PS)	Represents the sensitivity of a factor to changes within the system. Sum of the values in the columns.	
Indirect active sum i(AS)	Indirect relationships of the factors obtained by a matrix multiplication method.	The ADVIAN® method (Linss and Fried, 2009)
Indirect passive sum i(PS)	Indirect relationships of the factors obtained by a matrix multiplication method.	
Criticality (C)	Heavily influenced by other IFs and have a strong impact on other factors in the system. Geometric mean of iAS and iPS.	
Stability (S)	Indicates that the system is highly interconnected. Arithmetic mean of iAS and iPS.	
Integration (I)	Harmonic mean of indirect iAS and iPS which is subtracted from 100.	

2.2.3 Classification of factors and identification of pivots

The estimation of integration, criticality and stability gives an idea of the behavior of the system. However, to formulate recommendations a final classification based on all the indices that describe the system (direct and indirect effects) was proposed. The criteria established to perform the final classification is presented in Table 2.2. First class: factors suitable for changes, second class: positive factors and third class: neutral factors. This classification has the aim to identify factors that can be used to formulate recommendations, factors with negative impacts were not classified. Lastly, based on the classified factors, opportunities to improve the system were considered as pivots to develop recommendations. For this study, a pivot is a point that can be considered as support to promote a change or turn on the waste management system.

Table 2.2. Pivot identification based on the proposed classification rules.

Class	Selection rule	Classification rules
First Class Suitable	Low/Neutral C, high S high/neutral dAS, low dPS. Neutral C, low/neutral S, High dAS, low dPS	Suitable for extrinsic actions to improve performance of the whole system
Second Class Positive	Low/Neutral C, high dPS Low dAS and neutral PS	Positively affected by the system.
Third Class Neutral	Neutral C and S, PS and AS low/neutral	Neutral factors, no negative effects.

In the table AS: direct active sum, PS: direct passive sum, C: criticality, S: stability

2.3 Results

2.3.1 Systematic Literature Review: Impact Factor recognition for upper-middle income countries

The systematic literature review allowed to build an impact matrix based on the understanding of the barriers, challenges, and opportunities to improve MSW management. The performed systematic literature review resulted in 15 IFs (Table 2.3) initially classified as: financial, social, regulatory, institutional, and technical. The most cited factors were cost of investment, public involvement, and institutional coordination.

Table 2.3. List of impact factors and their definitions.

	Impact Factor	Classification	Definition	References
IF1	Cost of investment	Financial	Cost of investment of waste management projects	(Batista et al., 2021b; Bertolucci Paes et al., 2019; Ferronato and Torretta, 2019; Marshall and Farahbakhsh, 2013; Nevzorova and Kutcherov, 2019; Pan et al., 2015; Salmenperä et al., 2021; Santagata et al., 2021; UPME and BID, 2015; Zhang et al., 2019)
IF2	Public resources	Financial	Public resources assigned to waste management	(Bertolucci Paes et al., 2019; Fiksel et al., 2021; Marshall and Farahbakhsh, 2013; Nevzorova and Kutcherov, 2019)
IF3	Legal framework	Regulatory	Legal framework in waste management, policies, and existing regulations	(Batista et al., 2021b; Bertolucci Paes et al., 2019; Fiksel et al., 2021; Yukalang et al., 2017)
IF4	SWM institutions	Institutional	Number of institutions dedicated exclusively to solid waste management.	(Marshall and Farahbakhsh, 2013)
IF5	Policy implementation	Regulatory	Existing strategies to ensure the adequate implementation of solid waste management policies	(Batista et al., 2021b; De Sousa Jabbour et al., 2014)
IF6	Public involvement	Social	Public involvement and cooperation in source separation	(Batista et al., 2021b; Bertolucci Paes et al., 2019; Fiksel et al., 2021; Nevzorova and Kutcherov, 2019; Salmenperä et al., 2021; Santagata et al., 2021; Zhang et al., 2019)
IF7	Risk of investment	Financial	Risk of investment in waste management projects that can be unattractive due to its dependence on local conditions of implementation	(Ezeah and Roberts, 2012; Ferronato and Torretta, 2019)
IF8	Institutional coordination	Institutional	Coordination among sectors: academic-public-industries	(De Sousa Jabbour et al., 2014; Luiz Bufoni et al., 2016; Nevzorova and Kutcherov, 2019; Zhang et al., 2019)
IF9	SWM Infrastructure	Technical	Infrastructure, facilities, vehicles, alternatives for disposal, waste collecting points and space for new plants	(Fiksel et al., 2021; Patinvoh and Taherzadeh, 2019)
IF10	Technical capacity	Technical	Technological maturity and infrastructure in waste management	(Bertolucci Paes et al., 2019; Ferronato and Torretta, 2019; Yukalang et al., 2017)
IF11	Waste collectors	Social	Inclusion of waste collectors in the solid	(Ferronato and Torretta, 2019; Fiksel et al., 2021)

			waste management system	
IF12	Research and development (R&D)	Technical	Number of R&D projects in waste management and waste to energy.	(Chand Malav et al., 2020; Nevzorova and Kutcherov, 2019; Salmenperä et al., 2021; UPME and BID, 2015)
IF13	Fossil fuel-based economy	Financial	Dependence on fossil fuels due to low prices and technological maturity	(Bößner et al., 2019; Marshall and Farahbakhsh, 2013; Nevzorova and Kutcherov, 2019)
IF14	Local and national level balance	Institutional	Cooperation and communication among national and local development plans, policies and PGIRS	(Marshall and Farahbakhsh, 2013; Qing et al., 2010)
IF15	Waste-to-energy technologies	Financial Technical	Implementation of WtE technologies	(Bößner et al., 2019; Pan et al., 2015; Salmenperä et al., 2021)

In the table IF: impact factors, PGIRS: local waste management plans (in Spanish Plan Integral de Gestión de Residuos, WtE: waste-to-energy

The impact matrix built is presented in Figure 2.2. The systematic literature review considered only upper-middle income countries as an inclusion factor. As result, the identified relevant factors are a representation of waste management systems in upper-middle income countries. This impact matrix can be used by researchers as input for the combined impact analysis and participatory workshops. In the present study, the combined approach was applied to Sabana Centro province in Colombia as a case study.

Variable	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
	Cost of Investment	Public Resources	Legal Framework	SWM institutions	Policy implementation	Public involvement	Risk of investment	Institutional coordination	SWM Infrastructure	Technical capacity	Waste collectors	Research and Development	Fossil-fuel based economy	Local and national level balance	waste-to-energy technologies
Cost of Investment	**0**														
Public Resources		**0**													
Legal Framework			**0**												
SWM institutions				**0**											
Policy implementation					**0**										
Public involvement						**0**									
Risk of investment							**0**								
Institutional coordination								**0**							
SWM Infrastructure									**0**						
Technical capacity										**0**					
Waste collectors											**0**				
Research and Development												**0**			
Fossil-fuel based economy													**0**		
Local and national level balance														**0**	
waste-to-energy technologies															**0**

Figure 2.2 .Impact matrix built considering the impact factors selected by the systematic literature review.

2.3.2 The combined impact analysis and participatory approach: a case study for small urban cities in Colombia

To illustrate the application of the combined approach, this section presents the results of the case study applied to Sabana Centro, Colombia.

2.3.2.1 Filling the impact matrix: participatory workshops

A compilation of the matrices filled during participatory workshops was performed and the matrix multiplication method was applied in the Microsoft Excel application. Table 2.4 presents the results of the indices calculated during the application of the approach to Sabana Centro, Colombia a as a case study.

Table 2.4.Results of the indices calculated for the case study.

IFs	rd(AS)	rd(PS)	ri(AS)	ri(PS)	I	C	S
1. Cost of investment	100.0	29.6	100.0	24.8	62.4	49.8	60.3
2. Public resources	70.4	4.4	67.8	37.5	52.7	50.4	51.7
3. Legal framework	66.7	85.2	61.1	80.1	70.6	69.9	30.7
4. Waste management institutions	63.0	51.9	61.7	52.6	57.1	56.7	43.2
5. Policy implementation	48.1	85.2	46.7	100.0	73.4	68.4	36.3
6. Public involvement	37.0	74.1	36.5	82.8	59.6	54.9	49.4
7. Investment risk	63.0	29.6	55.7	30.0	42.8	40.9	61.0
8. Institutional coordination	51.8	70.4	46.2	87.1	66.7	63.4	39.6
9. Waste management infrastructure	59.3	55.6	57.2	36.3	46.8	45.6	55.6
10. Technical capacity	37.0	63.0	41.9	43.0	42.4	42.4	57.6
11. Waste collectors	25.9	51.9	27.7	77.5	52.6	46.3	59.2
12. Research and development	33.3	66.7	36.0	53.7	44.9	44.0	56.9
13. Fossil-fuel based economy	62.9	70.4	81.2	72.8	77.0	76.9	23.2
14. Local and national level balance	62.9	44.4	60.6	66.2	63.4	63.36	36.7
15. Waste-to-energy technologies	70.4	29.6	86.3	20.9	53.6	42.46	66.4

Measures for system behavior: (rd(AS)): relative direct active sum, (rd(PS)) relative indirect passive sum, (ri(AS)) relative indirect active sum, (ri(PS)) relative indirect passive sum, (I) integration, (C) criticality and (S) stability.

2.3.2.2 Calculation of indices: the impact analysis

The calculation of the indices must be followed by the identification of the ones with the highest criticality, integration and stability and contrast them with the local context to understand how they can help in the formulation of recommendations. Integration and criticality is presented in Figure 2.3a and Figure 2.3b. High integration and criticality was found for IF13 (fossil-fuel based economy), IF5 (policy implementation) and IF3 (legal framework). Highly integrative factors are the ones related to the complete system, changes in these factors can cause effects of large magnitude on the system and result in feedback connections (Guertler and Spinler, 2015). The most critical factors strongly influence the system but are also influenced by it, the reaction of the system to changes cannot be foreseen. As a result, recommendations should not be formulated based on these three factors. To analyze the relevance of this result, an analysis of the Colombian context regarding these factors was performed.

In Colombia, fossil fuels (IF13) are determinant for financial stability and economic development of the country. In fact, oil, natural gas, and their byproducts represented 55% of the total exports in 2013. Additionally, private investments in infrastructure in the sector during the last decade have been around 5% of total GDP, far above from other relevant sectors such as communications and transport which do not exceed 0.7% (UPME, 2015). According to the Mining-Energetic Planning Unit[6] (UPME), financial support for fossil fuels in Colombia increased up to $5 million in 2014. Only the first 8 months of 2014, these subsidies reached $500,000 (Semana, 2015). This situation is not expected to change in the next 30 years. Colombia produces two types of biofuels: bioethanol and biodiesel. Both are obtained from sugar cane and palm oil. In Colombia, 1.1 million liters of bioethanol and 1.7 of biodiesel are produced. Biofuels generated 25,000 direct jobs and 48,000 indirect jobs, this highlights the relevance of the development of biofuels in Colombia (Colmenares-Quintero et al., 2020).

According to the National Energy Plan[7] (PEN) 2020-2050, considering a disruptive scenario in which innovation to develop renewable technologies is the pillar, Colombia will be strongly dependent on fossil fuels by 2050. This means that, even under the most innovative scenario, the country foresees a very high dependence on fossil fuels. While oil, natural gas, and coal will still represent more than 55% of total energy supply by 2050, opportunities for biogas development will represent less than 12% (UPME (Unidad de Planeación Minero Energética), 2020). This scenario is supported by a strong legal framework for fossil fuels (IF3) considering royalties for the exploitation of non-renewable resources (Law 2056 of 2020). As a result, the marketplace in Colombia implies, for other waste treatment technologies, a strong

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[6] In spanish, Unidad de Planeación Minero-energética

[7] In spanish, Plan Energético Nacional

competition with more established fossil fuel and hydropower. Based on this reasoning, direct changes in non-renewable resources actual legal framework are not recommended.

On the other hand, legal framework for solid waste management in Colombia is based on CONPES[8] 3874 with clear milestones and goals. However, even though there is a national policy, the strategies for its implementation are ambiguous (IF5). These strategies are still unclear due to a missing link with the private sector and the existing institutions dedicated to waste management. Energy service companies (ESCO) are dedicated to design, build, and arrange financing for projects that reduce energy costs. The creation of ESCOs in Colombia can help in building waste treatment capacity.

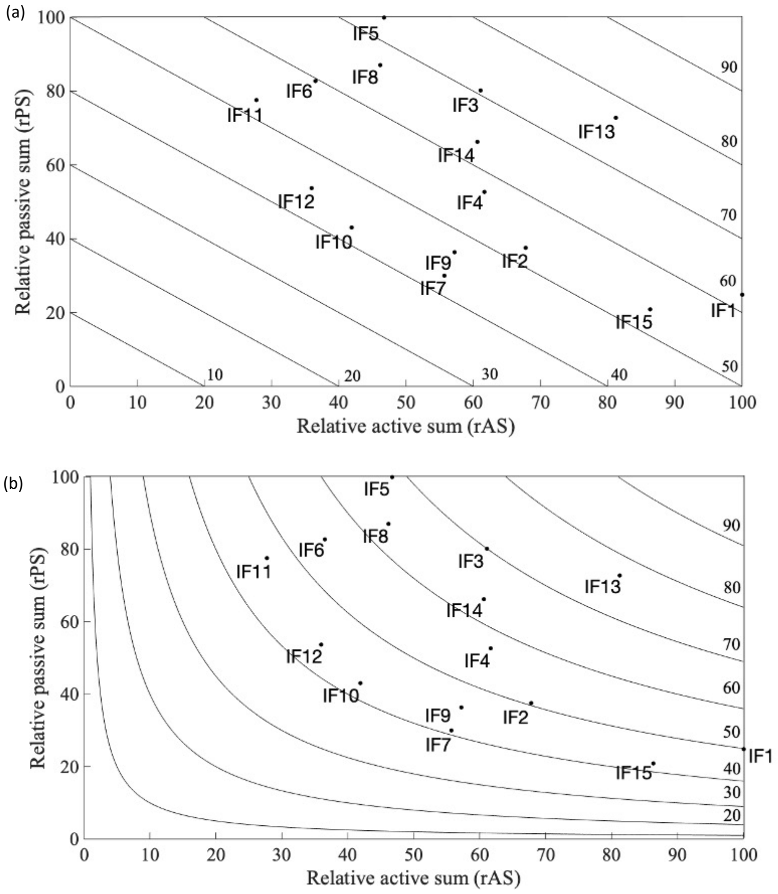

Figure 2.3. Factors highly (a) integrative and (b) critical in Sabana Centro, Colombia

IFs: (1) cost of investment, (2) public resources, (3) legal framework, (4) waste management institutions, (5) policy implementation, (6) public involvement, (7) investment risk (8), institutional coordination, (9) waste

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[8] In spanish, Consejo Nacional de Política Económica y Social

management infrastructure, (10) technical capacity (11) waste collectors, (12) research and development, (13) fossil-fuel based economy (14) local and national level balance and (15) waste-to-energy.

Stability is presented in Figure 2.4 for Sabana Centro, Colombia. IFs with high stability have the highest contribution to balance of the system and can hardly be changed by the system. According to the results, the most stable factors are waste-to-energy technologies (IF15), investment risk (IF7) and cost of investment (IF1). As a result, recommendations for Sabana Centro must be based on these factors.

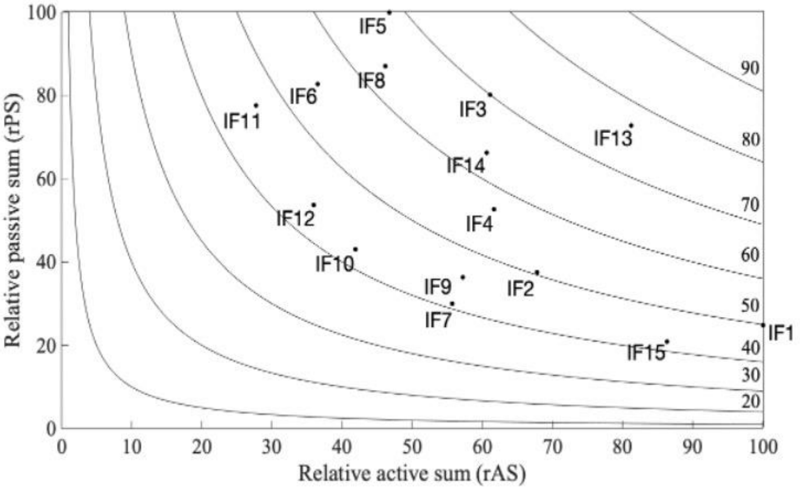

Figure 2.4. Stability of impact factors in Sabana Centro, Colombia.

IFs: (1) cost of investment, (2) public resources, (3) legal framework, (4) waste management institutions, (5) policy implementation, (6) public involvement, (7) investment risk (8), institutional coordination, (9) waste management infrastructure, (10) technical capacity (11) waste collectors, (12) research and development, (13) fossil-fuel based economy (14) local and national level balance and (15) waste-to-energy.

WtE technologies are processes such as gasification, anerobic digestion, combustion, pyrolysis, or landfill gas recovery, that recover energy from non-recyclable wastes and produce heat, electricity, or fuel (Shareefdeen et al., 2015). Nowadays, WtE is the preferred treatment option for waste that cannot be recycled (Van Caneghem et al., 2019). As a result, WtE technologies have a critical role in the improvement of MSW in developing countries. For instance, several countries around the world have reported advances in MSW management through the promotion of WtE (Chen et al., 2010; Patinvoh and Taherzadeh, 2019; Surendra et al., 2014).

In Colombia, these technologies are not successfully implemented yet. The law 1715 issued in 2014 regulates financial incentives for private investments regarding Non-Conventional Renewable Energy (NCRE). To receive benefits such as a 50% annual reduction of total investment, an exemption of added value taxes, and import tariffs, and an accelerated depreciation; private companies must receive an approval from the UPME and the Ministry of the Environment. Article 10 of the law 1715 regulates the creation of a "Non-conventional Renewable Energy and Efficient Energy Management Fund", FENOGE, supervised by the Ministry of Energy and Mining. FENOGE has the aim of financing, management and executing programs and projects aligned with NCRE. To apply for funding, private companies and governmental institutions must present a technical and financial proposal, this proposal is evaluated by FENOGE, and they decide if the project is qualified for partially or full refundable financing or partially or full non-refundable financing (FENOGE, 2021). These incentives are the only ones existing today in Colombia. As a result, additional financing sources are necessary in Colombia. These strategies have worked in different countries such as Sweden, China, and Indonesia. Multiple financial schemes are essential to reduce risk and cost of investment associated to MSW management.

According to the results of criticality, stability, and integration for Sabana Centro, recommendations must be developed based on the factors: waste-to-energy technologies (IF15), investment risk (IF7) and cost of investment (IF1). However, an extensive classification of the factors is proposed in the following section to provide insights for specific recommendations that can help Sabana Centro in its way towards sustainable waste management systems implementation.

2.3.3 Classification of factors: development of recommendations for Sabana Centro

Figure 2.5 shows a framework to improve MSW management in Sabana Centro based on the results of the combined approach. First, the classification of factors according to Table 2.2 is discussed. These factors are the ones suitable for changes. Then, based on these factors, 5 pivots were identified: multiple funding schemes, Public-Private Partnerships (PPP), Public

Awareness, waste-to-energy, and national-local level balance. The combined approach of participatory workshops and impact analysis developed here also enabled the identification of pivots and the development of recommendations specifically formulated for Sabana Centro, Colombia. The pivots are the starting point for changes that can result in positive effects to improve how MSW is currently managed in Sabana Centro. By analyzing the local context, this study led to know the real situation of the province. This ensures that the recommendations developed could potentially be used as a base for decision makers to develop MSW management policies.

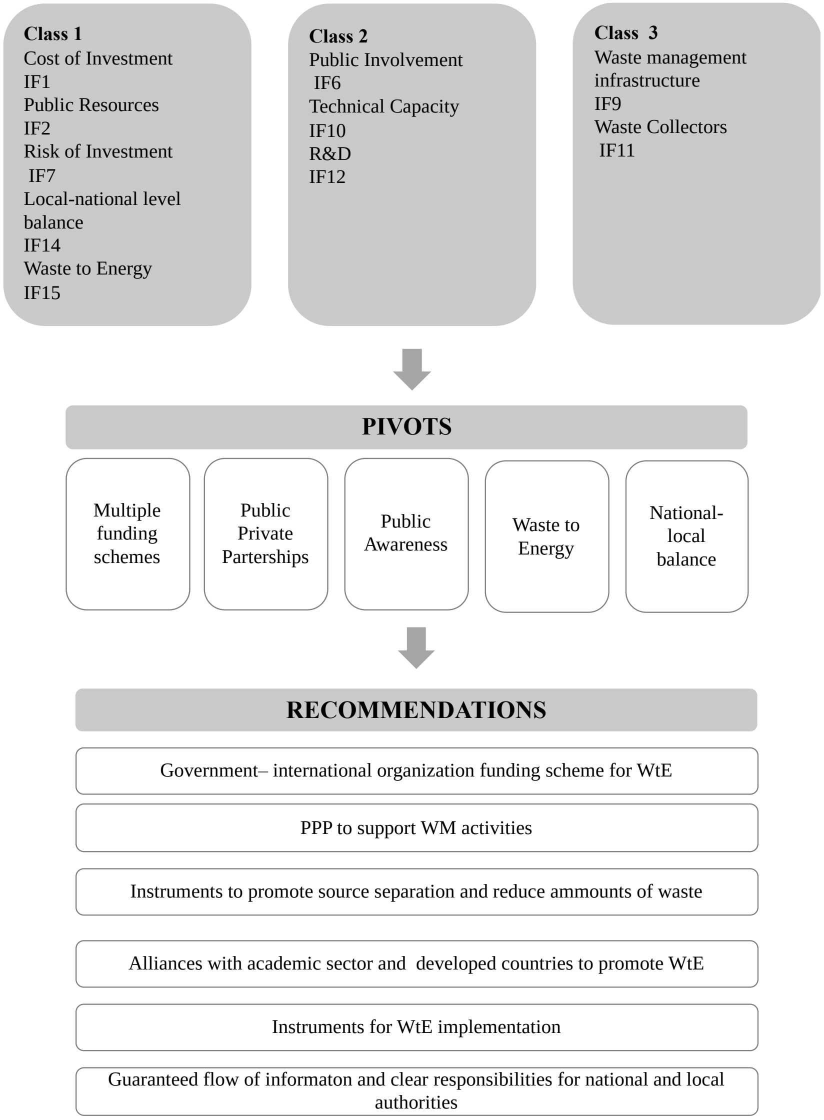

Figure 2.5. Recommendations for Sabana Centro based on the proposed classification.

Multiple funding schemes are needed to promote waste treatment technologies: Waste treatment technologies, such as WtE are more commonly applied in developed countries (Mmereki et al., 2016). In developing countries these technologies are not viable due to their high capital investment. For instance, biological treatments are applied at small-scales and some existing facilities present incompatibilities in terms of process design and characteristics of the waste (Mmereki et al., 2016). Feasibility of WtE depend on waste-related and demographic factors, while financial viability is based on financial resources and potential revenues (Abdallah et al., 2020). Government funding, the private sector inclusion in waste management, and the financial support of international organizations is needed to boost the implementation of waste treatment technologies, especially in developing countries where primitive treatment technologies and disposal methods are still in place (Mmereki et al., 2016). Sabana Centro is not the exception, even though municipalities have the intention to implement treatment technologies and avoid disposing MSW in sanitary landfills, lack of funding to support these projects is identified as a main barrier to this transition. FENOGE is a successful case of a government funding program in Colombia. By 2020, the law 1715 of 2014 and the creation of FENOGE have promoted 294 renewable energy projects, represented mainly by solar and wind energy (Alfonso López Suárez, 202AD). The government of Colombia needs to dedicate efforts to develop programs in collaboration with the private sector to reduce the high cost and risk of investment of waste treatment technologies. It is important to consider that in Colombia and other developing countries, MSW management activities are not given higher priority by planners, there are other issues which may take precedence, such as health, education, and hunger (Mmereki et al., 2016). As a result, a multiple funding scheme could help in the development of waste treatment projects in Sabana Centro, reducing the risk and cost of investment associated to these kinds of projects that nowadays must be covered by municipalities.

Public-Private Partnerships must be created to support waste management activities: PPPs are often capable or reducing the cost of waste management, improving service quality, and making a formal link between the public and the private sector to improve efficiency (Spoann et al., 2019). In most developed countries, there is sufficient public-private partnerships and expertise to implement waste management technologies. They have integrated and implemented policy frameworks that consider environmental, technical, institutional, and financial aspects (Mmereki et al., 2016). In developing countries, the absence of technological waste treatment facilities has led local governments to create privately built MSW facilities through PPPs (Dolla and Laishram, 2021). Regarding waste collection and treatment, China is another successful case of MSW management development with the support of the private sector. The private sector plays an important role in MSW management in China specially in projects which are expensive to build and operate (Chen et al., 2010). Deus et al. (2017) proposed the creation of public consortia or the privatization of final disposal systems to promote adequate MSW disposal in small municipalities in Brazil (Deus et al., 2017). Additionally, according to the World Bank initiatives to promote micro-enterprise can help regularize the informal sector (The World Bank, 2021b). Nowadays, Sabana Centro uses compost technologies to treat the organic fraction of MSW. However, this service is provided by private companies and the municipality must cover treatment costs. PPPs in Colombia could foster the inclusion of the private sector in the construction and operation of waste treatment facilities. Additionally, municipal authorities could work with ESCOs to develop programs to support renewable energy generation.

Public involvement in source separation activities can help preparing waste for treatment technologies: In developed countries, different waste treatment technologies have been applied successfully. Thermal and biological conversion of waste through different methods have been reported. The success of these processes is due to effective source separation and recycling policies (Mmereki et al., 2016). However, high costs associated to recycling and source separation activities hinder the transition to more effective treatment technologies in developing countries. Sabana Centro have demonstrated the essential role of source separation in the effectiveness of MSW management. Cajicá is an example of source separation. Chía and Zipaquirá are currently implementing source separation policies and starting organic collection routes to send waste to compost. Even though Colombia, and even

Cajicá, consider a flat rate method to charge for MSW management, Cajicá contemplates an additional charge to penalize households that do not comply with local separation policies. This has helped Cajicá in the achievement of a recycling rate higher than 70%. To improve MSW in Sabana Centro, the remaining municipalities must apply source separation policies and introduce waste management charges. This task can be achieved by encouraging public involvement with the help of television and social media, involving citizens in management activities and inclusion of solid waste management as syllabus at school level (Chand Malav et al., 2020).

Waste to energy technologies are essential to improve the efficiency of waste management systems: WtE technologies offer multiple benefits in terms of social and environmental aspects. They generate energy from renewable sources, decreasing the dependance on fossil fuels. waste-to-energy can reduce MSW volume and produce beneficial electricity (Chand Malav et al., 2020). In Colombia, waste-to-energy technologies can be employed to progressively substitute landfilling method, decrease the amounts of waste, and reduce environmental pollution. Even though the law 1715 established tax incentives, the integration of biomass-based projects has not been stimulated, especially for anaerobic digestion of MSW. Additionally, there are still subsidies for fossil-fuel based energy generation that makes the price of renewable energy too high to be a viable energy option. It is estimated that eliminating fossil-fuel subsidies globally can reduce GHG emissions by 6% and benefit the development of renewable energy (Pan et al., 2015). Nowadays, eliminating conventional subsidies and modifying legal framework on fossil fuels is not possible, financial stability of the country depend on the incomes generated by this market. To implement waste-to-energy, Sabana Centro will also benefit from R&D projects with the academic sector and developed countries to increase technical capacity in waste-to-energy.

Clear responsibilities and roles must be assigned to ensure balance between the government and the municipalities: According to Mmereki et al. (2016) the lack of clear roles and responsibilities among stakeholders is a relevant difference between developed and developing countries (Mmereki et al., 2016). This mainly due to the lack of proper organizational structures within municipalities and the lack of ground rules for the allocation of resources and monitoring institutions. In Sabana Centro, some municipalities show an alignment between their PGIRS and the national solid waste management policy. For instance, the municipalities of Cajicá and Chía have presented organized schemes to separate and manage MSW. The program "caneca verde" implemented first in Cajicá and then in Chia has the aim of giving special containers to dispose organic fraction of municipal solid waste to send this fraction to be composted. The program also formulates a framework to ensure source separation of organic and recyclable waste and the public involvement through education campaigns. This program has been a success in Cajicá for many years and nowadays is starting in Chía. However, there are other municipalities that are focused only on the recovery of recyclables, such as Tocancipá. According to the PGIRS formulated in 2020 (Municipio de Tocancipá, 2020), the municipality only recovers recyclables and organics are not separated and sent to landfills. An alternative for using composting was proposed but there are no clear initiatives yet. To ensure an improvement in MSW management in Sabana Centro, municipalities should develop PGIRS that must be aligned with the national policy for solid waste management CONPES 3874. Municipalities in Sabana Centro must collaborate in the formulation of their PGIRS, to ensure compliance of national policies from the lower levels. On the other hand, the government of Colombia should empower local government to manage waste more efficiently.

2.4 Conclusions

The present study aimed to propose a combined approach to identify, classify and analyze the factors that affect the management of municipal solid waste in upper-middle income countries, leading to the formulation of recommendations for Sabana Centro, Colombia as a case study. The combined approach considered not only an extensive literature review but also an impact analysis combined with participatory workshops to gain knowledge about local MSW management from relevant stakeholders and to classify the factors and identify the ones that can be useful for immediate changes that can be translated into an improved system. The approach was applied in Sabana Centro, Colombia as case study and five recommendations were formulated: i) due to the lack of financial stability of small municipalities, multiple funding schemes are needed to promote waste treatment technologies, ii) Public-Private Partnerships must be created to support waste management activities in municipalities, iii) public involvement in source separation activities is necessary to improve MSW management, Cajicá is an example inside Sabana Centro, iv) the implementation of waste-to-energy technologies is essential to improve the efficiency of waste management systems, multiple funding schemes and the involvement of the private sector is necessary to start this transition, v) local waste management plans (PGIRS) must be aligned among municipalities and with national waste management policy. Clear responsibilities and roles must be assigned to ensure compliance from the lower levels. The proposed combined analysis can be applied in upper-middle income countries as a tool that can support decision-making processes to improve MSW management systems.

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References

Abdallah, M., Arab, M., Shabib, A., El-Sherbiny, R., El-Sheltawy, S., 2020. Characterization and sustainable management strategies of municipal solid waste in Egypt. Clean Technol Environ Policy 22, 1371–1383. https://doi.org/10.1007/s10098-020-01877-0

Abushammala, M.F.M., Qazi, W.A., 2021. Financial feasibility of waste-to-energy technologies for municipal solid waste management in Muscat, Sultanate of Oman. Clean Technol Environ Policy 23, 2011–2023. https://doi.org/10.1007/s10098-021-02099-8

Alfonso López Suárez, 202AD. Con 294 proyectos, Colombia transita a energías limpias [WWW Document]. Portafolio. URL https://www.portafolio.co/economia/con-294-proyectos-colombia-transita-a-energias-limpias-545001 (accessed 2.19.21).

Anwar, S., Elagroudy, S., Abdel Razik, M., Gaber, A., Bong, C.P.C., Ho, W.S., 2018. Optimization of solid waste management in rural villages of developing countries. Clean Technol Environ Policy 20, 489–502. https://doi.org/10.1007/s10098-018-1485-7

Batista, M., Goyannes Gusmão Caiado, R., Gonçalves Quelhas, O.L., Brito Alves Lima, G., Leal Filho, W., Rocha Yparraguirre, I.T., 2021a. A framework for sustainable and integrated municipal solid waste management: Barriers and critical factors to developing countries. J Clean Prod 312, 127516. https://doi.org/10.1016/j.jclepro.2021.127516

Batista, M., Goyannes Gusmão Caiado, R., Gonçalves Quelhas, O.L., Brito Alves Lima, G., Leal Filho, W., Rocha Yparraguirre, I.T., 2021b. A framework for sustainable and integrated municipal solid waste management: Barriers and critical factors to developing countries. J Clean Prod 312. https://doi.org/10.1016/j.jclepro.2021.127516

Bertolucci Paes, L.A., Stolte Bezerra, B., Mattos Deus, R., Jugend, D., Gomes Battistelle, R.A., 2019. Organic solid waste management in a circular economy perspective - A systematic review and SWOT analysis. J Clean Prod 239, 118086. https://doi.org/10.1016/j.jclepro.2019.118086

Bößner, S., Devisscher, T., Suljada, T., Ismail, C.J., Sari, A., Mondamina, N.W., 2019. Biomass and Bioenergy Barriers and opportunities to bioenergy transitions : An integrated , multi- level perspective analysis of biogas uptake in Bali. Biomass Bioenergy 122, 457–465. https://doi.org/10.1016/j.biombioe.2019.01.002

Chand Malav, L., Yadav, K.K., Gupta, N., Kumar, S., Sharma, G.K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q.B., Yadav, S., Bhattacharyya, S., Yadav, V.K., Bach, Q.V., 2020. A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. J Clean Prod 277, 123227. https://doi.org/10.1016/j.jclepro.2020.123227

Chen, X., Geng, Y., Fujita, T., 2010. An overview of municipal solid waste management in China. Waste Management 30, 716–724. https://doi.org/10.1016/j.wasman.2009.10.011

Colmenares-Quintero, R. F., Rico-Cruz, C. J., Stansfield, K. E., & Colmenares-Quintero, J. C. (2020). Assessment of biofuels production in Colombia. In Cogent Engineering (Vol. 7, Issue 1). Cogent OA. https://doi.org/10.1080/23311916.2020.1740041

Coventry, Z.A., Tize, R., Karunanithi, A.T., 2016. Comparative life cycle assessment of solid waste management strategies. Clean Technol Environ Policy 18, 1515–1524. https://doi.org/10.1007/s10098-015-1086-7

De Sousa Jabbour, A.B.L., Jabbour, C.J.C., Sarkis, J., Govindan, K., 2014. Brazil's new national policy on solid waste: Challenges and opportunities. Clean Technol Environ Policy 16, 7–9. https://doi.org/10.1007/s10098-013-0600-z

Deus, R.M., Battistelle, R.A.G., Silva, G.H.R., 2017. Scenario evaluation for the management of household solid waste in small Brazilian municipalities. Clean Technol Environ Policy 19, 205–214. https://doi.org/10.1007/s10098-016-1205-0

Dolla, T., Laishram, B., 2021. Effect of energy from waste technologies on the risk profile of public-private partnership waste treatment projects of India. J Clean Prod 284, 124726. https://doi.org/10.1016/j.jclepro.2020.124726

Ezeah, C., Roberts, C.L., 2012. Analysis of barriers and success factors affecting the adoption of sustainable management of municipal solid waste in Nigeria. J Environ Manage 103, 9–14. https://doi.org/10.1016/j.jenvman.2012.02.027

FENOGE, 2021. ¿Qué es FENOGE? [WWW Document]. Fondo de Energías No Convencionales y Gestión Eficiente de la Energía. URL https://fenoge.com/quienes-somos/ (accessed 2.11.21).

Ferronato, N., Torretta, V., 2019. Waste mismanagement in developing countries: A review of global issues. Int J Environ Res Public Health 16. https://doi.org/10.3390/ijerph16061060

Fiksel, J., Sanjay, P., Raman, K., 2021. Steps toward a resilient circular economy in India. Clean Technol Environ Policy 23, 203–218. https://doi.org/10.1007/s10098-020-01982-0

Guertler, B., Spinler, S., 2015. Supply risk interrelationships and the derivation of key supply risk indicators. Technol Forecast Soc Change 92, 224–236. https://doi.org/10.1016/j.techfore.2014.09.004

Inglezakis, V.J., Moustakas, K., Khamitova, G., Tokmurzin, D., Sarbassov, Y., Rakhmatulina, R., Serik, B., Abikak, Y., Poulopoulos, S.G., 2018. Current municipal solid waste management in the cities of Astana and Almaty of Kazakhstan and evaluation of alternative management scenarios. Clean Technol Environ Policy 20, 503–516. https://doi.org/10.1007/s10098-018-1502-x

Jisc, 2012. Planning a participatory workshop [WWW Document]. JISC. URL https://www.jisc.ac.uk/guides/planning-a-participatory-workshop (accessed 10.21.20).

Krieger, M., Hoischen-taubner, S., Emanuelson, U., Blanco-penedo, I., Joybert, M. De, Duval, J.E., Sjöström, K., Jones, P.J., Sundrum, A., 2017. Capturing systemic interrelationships by an impact analysis to help reduce production diseases in dairy farms. Agric Syst 153, 43–52. https://doi.org/10.1016/j.agsy.2017.01.022

Linss, V., Fried, A., 2010. The ADVIAN® classification - A new classification approach for the rating of impact factors. Technol Forecast Soc Change 77, 110–119. https://doi.org/10.1016/j.techfore.2009.05.002

Linss, V., Fried, A., 2009. Advanced Impact Analysis : the ADVIAN ® method - an enhanced approach for the analysis of impact strengths with the consideration of indirect relations. Papers and Preprints of the Department of Innovation Research and Sustainable Resource Management (BWL IX). Chemnitz University of Technology.

Luiz Bufoni, A., Basto Oliveira, L., Pinguelli Rosa, L., 2016. The declared barriers of the large developing countries waste management projects : The STAR model 52, 326–338. https://doi.org/10.1016/j.wasman.2016.03.023

Makarichi, L., Jutidamrongphan, W., Techato, K. anan, 2018. The evolution of waste-to-energy incineration: A review. Renewable and Sustainable Energy Reviews 91, 812–821. https://doi.org/10.1016/j.rser.2018.04.088

Marshall, R.E., Farahbakhsh, K., 2013. Systems approaches to integrated solid waste management in developing countries. Waste Management 33, 988–1003. https://doi.org/10.1016/j.wasman.2012.12.023

Martins, R., Cherni, J.A., Videira, N., 2018. 2MBio, a novel tool to encourage creative participatory conceptual design of bioenergy systems – The case of wood fuel energy systems in south Mozambique. J Clean Prod 172, 3890–3906. https://doi.org/10.1016/j.jclepro.2017.05.062

Mmereki, D., Baldwin, A., Li, B., 2016. A comparative analysis of solid waste management in developed, developing and lesser developed countries. Environmental Technology Reviews. https://doi.org/10.1080/21622515.2016.1259357

Municipio de Tocancipá, 2020. Plan de manejo integral de residuos sólidos 192.

Nevzorova, T., Kutcherov, V., 2019. Barriers to the wider implementation of biogas as a source of energy : A state-of-the-art review. Energy Strategy Reviews 26, 100414. https://doi.org/10.1016/j.esr.2019.100414

Pan, S., Alex, M., Huang, I., Liu, I., Chang, E., Chiang, P., 2015. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system : a review. J Clean Prod 108, 409–421. https://doi.org/10.1016/j.jclepro.2015.06.124

Patinvoh, R.J., Taherzadeh, M.J., 2019. ScienceDirect Challenges of biogas implementation in developing countries. Curr Opin Environ Sci Health 12, 30–37. https://doi.org/10.1016/j.coesh.2019.09.006

Qing, D., Keat, S., Gersberg, R.M., 2010. Municipal solid waste management in China : Status , problems and challenges. J Environ Manage 91, 1623–1633. https://doi.org/10.1016/j.jenvman.2010.03.012

Rojas, J.D., Vélez Betancourth, R.N.O.D., Gutiérrez Buitrago, A., Mazeneth, A., Carolina, P.M., 2020. Informe de Calidad de Vida 2019. Chía, Collombia.

Salmenperä, H., Pitkänen, K., Kautto, P., Saikku, L., 2021. Critical factors for enhancing the circular economy in waste management. J Clean Prod 280. https://doi.org/10.1016/j.jclepro.2020.124339

Santagata, R., Ripa, M., Genovese, A., Ulgiati, S., 2021. Food waste recovery pathways: Challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment. J Clean Prod 286, 125490. https://doi.org/10.1016/j.jclepro.2020.125490

Schianetz, K., Kavanagh, L., 2008. Sustainability Indicators for Tourism Destinations : A Complex Adaptive Systems Approach Using Systemic Indicator Systems. Journal of Sustainable Touris 9582, 601–628. https://doi.org/10.2167/jost766.0

Sebastian, R.M., Kumar, D., Alappat, B., 2020. Mapping incinerability of municipal solid waste in Indian sub-continent. Clean Technol Environ Policy 22, 91–104. https://doi.org/10.1007/s10098-019-01771-4

Semana, 2015. El problema de subsidiar los combustibles fósiles [WWW Document]. Semana. URL https://www.semana.com/economia/articulo/el-problema-subsidiar-combustibles-fosiles-colombia-mundo/217234/ (accessed 2.24.21).

Shareefdeen, Z., Elkamel, A., Tse, S., 2015. Review of current technologies used in municipal solid waste-to-energy facilities in Canada. Clean Technol Environ Policy 17, 1837–1846. https://doi.org/10.1007/s10098-015-0904-2

Spoann, V., Fujiwara, T., Seng, B., Lay, C., Yim, M., 2019. Assessment of public-private partnership in municipal solid waste management in Phnom Penh, Cambodia. Sustainability (Switzerland) 11. https://doi.org/10.3390/su11051228

Superintendencia de Servicios Públicos Domiciliarios, 2019. Disposición Final de Residuos Sólidos Informe Nacional– 2018. Colombia.

Surendra, K.C., Takara, D., Hashimoto, A.G., Kumar, S., 2014. Biogas as a sustainable energy source for developing countries : Opportunities and challenges. Renewable and Sustainable Energy Reviews 31, 846–859. https://doi.org/10.1016/j.rser.2013.12.015

The World Bank, 2021a. World Bank Country and Lending Groups [WWW Document]. Data (Basel).

The World Bank, 2021b. Municipal Solid Waste (MSW) PPPs [WWW Document]. URL https://ppp.worldbank.org/public-private-partnership/sector/solid-waste/FR (accessed 2.12.21).

Tsai, F.M., Bui, T.D., Tseng, M.L., Wu, K.J., Chiu, A.S., 2020. A performance assessment approach for integrated solid waste management using a sustainable balanced scorecard approach. J Clean Prod 251, 119740. https://doi.org/10.1016/j.jclepro.2019.119740

UPME, 2015. Evaluación de la contribución económica del sector de hidrocarburos colombiano frente a diversos escenarios de producción. Upme 1–239.

UPME, BID, 2015. Integración de las energías renovables no convencionales en Colombia, Ministerio de Minas y Energía.

UPME (Unidad de Planeación Minero Energética), 2020. Plan Energético Nacional 2020-2050 2015.

Van Caneghem, J., Van Acker, K., De Greef, J., Wauters, G., Vandecasteele, C., 2019. Waste-to-energy is compatible and complementary with recycling in the circular economy. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-019-01686-0

Vester, F., 2007. The Art of Interconnected Thinking: Tools and Concepts for a New Approach to Tackling Complexity. Munich.

Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering, Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering. Karlskrona, Sweden. https://doi.org/10.1145/2601248.2601268

Yukalang, N., Clarke, B., Ross, K., 2017. Barriers to Effective Municipal Solid Waste Management in a Rapidly Urbanizing Area in Thailand. Int J Environ Res Public Health 9–14. https://doi.org/10.3390/ijerph14091013

Zhang, A., Venkatesh, V.G., Liu, Y., Wan, M., Qu, T., Huisingh, D., 2019. Barriers to smart waste management for a circular economy in China. J Clean Prod 240, 118198. https://doi.org/10.1016/j.jclepro.2019.118198

Chapter 3

Improving dry anaerobic methane production from OFMSW by co-digestion and fungal pretreatment strategies

In Chapter 2, a combined approach to identify the most relevant factors that affect MSW management systems in Sabana Centro (Colombia) was applied and recommendations were formulated to support local authorities in decision-making processes. One of the recommendations is the implementation of waste-to-energy technologies as an essential strategy to improve the efficiency of waste management systems. However, in upper-middle income countries, lack of technical knowledge and funding sources to start waste-to-energy projects are main barriers. In Colombia, organic fraction represents the majority of MSW. Accordingly, technologies such as anaerobic digestion are a suitable option for Sabana Centro. However, only composting treatments are applied in the region and there is an absence of projects to explore dry anaerobic digestion of local OFMSW. This chapter presents a scientific paper submitted to the journal Energy for Sustainable Development and proposed an evaluation of laboratory scale dry anaerobic digestion experiments using locally available organic waste (OFMSW, Municipal Grass Waste, and cattle manure) at mesophilic conditions.

Two different municipalities from Sabana Centro were considered to perform the experiments. Cajicá is the leader of the province in organics recovery and treatment. Source separation policies have existed for 17 years and citizens in general have a good behavior towards waste classification. Organics in Cajicá include fruit, vegetables, eggshells, cooked food products, and uncooked meat. Chía is the second municipality with the highest organics recovery rate. Nowadays, Chía has implemented a pilot plan with 3 different organics collection routes. However, there are still some limitations regarding general separation at source behaviors. Organic fraction in Chía is composed by fruit, vegetables, and eggshells; cooked food products and uncooked meat are not allowed. It is known from experiences in the province that the presence of meat and bones greatly delay the process of composting. Experiments presented in this chapter intended to identify differences in the performances of dry AD when samples from Chía and Cajicá are processed. This to analyze the effect of source separation policies in biogas production for OFMSW in Sabana Centro. Additionally, strategies such as co-digestion and a fungal pretreatment were explored to study its effect on biogas and methane yields.

Lab-scale experiments using organic waste from Sabana Centro are essential to gain knowledge about process behavior, efficiencies, and conditions. Experiments presented in this chapter were developed as part of a project "Evaluation of a municipal waste-to-energy biogas plant using solid-state anaerobic digestion for Sabana Centro, Colombia" funded by the call 829 "Colombia Bio" of the Ministry of Science, Technology, and Innovation of Colombia (Minciencias), with the participation of The Botanical Garden of Bogota (JBB[9]), ASOCENTRO[10] (Asociación de Municipios de Sabana Centro, and the Public Services Companies of Cajicá (EPC[11]) and Chía (EMSERCHIA[12]). Results of lab-scale evaluation were used at pilot-scales and then to perform a participatory process design for Sabana Centro.

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[9] In Spanish, Jardín Botánico de Bogtá

[10] In Spanish, Asociación de Municipios de Sabana Centro

[11] In Spanish, Empresa de Servicios Públicos de Cajicá

[12] In Spanish, Empresa de Servicios Públicos de Chía

Improving dry anaerobic methane production from OFMSW by co-digestion with grass waste and pretreatment with white rot fungi[13]

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Abstract

Anaerobic digestion (AD) is a process that can provide both clean energy and environmentally sustainable management of organic wastes. However, dry anaerobic digestion is susceptible to inhibitions and still has technological hurdles that limit its implementation. The study of operational parameters for the treatment of OFMSW in many places of the world is conducted, but the effect of the substrate composition is poorly understood. The present study evaluated strategies to enhance methane production from two different types of OFMSW, provided by two municipalities of Sabana Centro (Colombia), that are distinguished from each other by the presence (Cajicá, W1) and absence (Chia, W2) of meat residues. For both residues, higher methane production was achieved when the lowest substrate to inoculum ratio was used. ACoD with MGW enhanced biogas production with both OFMSW, increasing 61% of production when non- meat residues were used, and always being necessary for production on residues with meat. Fungal pretreatment did not increase methane yields as expected from experiences in other studies, probably due to pH drops and the accumulation of potential toxic inhibitors. In conclusion, as organic waste composition is critical to achieve an efficient dry AD performance, results presented in this work highlights the need to consider how much nature of the substrate influences the process. Potentially, if decision-making by local authorities includes better source separation policies for waste treatment alternatives, ACoD could be an effective strategy that can be applied in municipalities to treat OFMSW.

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[13] Submitted version, Energy for Sustainable Development

3.1 Introduction

Currently, countries around the world search for sustainable waste management systems that can be coupled with energy generation. Inadequate waste disposal is a limiting factor to achieving this transition; growing economies must deal with simultaneous and sharp increases of waste production and energy demand (Hansen et al., 2007; Mayer et al., 2019). Waste-to-energy technologies can reduce the use of fossil energy sources and air pollution, allowing to reduce the amounts of waste that must be disposed in landfills (Ward et al., 2008). It is estimated that the world will produce around 3.4 billion metric tons of MSW by 2050 (Panigrahi and Dubey, 2019) and as landfills are the most common disposal strategy in upper-middle income countries, environmental authorities face significant operational challenges. The Organic Fraction of Municipal Solid Waste (OFMSW) represents most of the Municipal Solid Waste (MSW) in most countries (Franca and Bassin, 2020); 60% in Colombia, 53% in China, and 46% global (Panigrahi and Dubey, 2019). Municipal Grass Waste (MGW) is part of MSW, it represents around 13% by weight, and has no significant commercial uses or industrial relevance (Danial et al., 2020). Nowadays, around 7% of MGW generated globally is still landfilled and its management is also a challenge for municipalities (Danial et al., 2020). However, grass belongs to lignocellulosic biomass and could be profitably used to produce bioenergy (Bedoić et al., 2019).

Anaerobic digestion (AD) is the best biological treatment option for the OFMSW in terms of economic and environmental performance (Panigrahi and Dubey, 2019). Through AD, organic materials can be converted into valuable end and by-products such as biogas and fertilizers (Bouaita et al., 2022; Zhou et al., 2021). The process is known as anaerobic mono-digestion (AMoD) if only one biomass source is treated, and anaerobic co-digestion (ACoD) when two or more substrates are processed. The application of AD can provide both an organic waste management alternative, and renewable energy source to cover a growing energy demand (Hallaji et al., 2019). However, it is undeveloped in Latin American countries (Fan et al., 2017; Silva-Martínez et al., 2020). Even though wet AD is the most implemented worldwide, there is a recent interest in dry AD since it has multiple benefits: reactor volumes can be reduced, energy consumption is lower, pump-free filling of digesters, transport costs are reduced since digested volumes are decreased, and digestates are easier to handle (André et al., 2018; Jiang et al., 2019; Nasir et al., 2020; Silva-Martínez et al., 2020). However, the development of full-scale dry AD is still defiant since the accumulation of Volatile Fatty Acids (VFA) usually occurs in reactors, leading to inhibition and a possible failure of the process (Jiang et al., 2019). Furthermore, food waste and the OFMSW present high volatile solids contents which causes rapid hydrolysis during the process resulting in severe acidification (Wang et al., 2014).

Different strategies have been proposed to improve methane generation and the stability of the process. The most relevant are the pretreatment of substrates and ACoD (Kainthola et al., 2019). On the one hand, different pretreatment techniques such as thermal and chemical, have been studied at lab and pilot-scales. Among pretreatments, biological processes consume less energy and chemicals than other methods, avoiding the generation of substances with inhibitory effects and having lower environmental impacts (Li et al., 2019). Biological pretreatments imply the use of bacteria, fungi, or enzymes. The use of partially purified lipase from *Staphylococcus pasteuri* COM-4A (Ning et al., 2016), the White Rot Fungi (WRF) *Pleurotus ostreatus,* and *Trichoderma reesei* (Mustafa et al., 2016) have been proposed to digest substrates different from the OFMSW. Brown-rot fungi can be used to pretreat lignocellulosic substrates. However, WRF are generally preferred as they are more efficient in delignification (Rouches et al., 2016). On the other hand, ACoD is usually implemented as a strategy to improve the stability of the process and avoid inhibitions (André et al., 2018; Wang et al., 2014). However, there are only a few studies regarding the use of MGW as a co-substrate during dry AD of OFMSW (Tyagi et al., 2018).

In this context, the present study aimed to evaluate dry AD of two OMFSW with different waste compositions to determine if some strategies like ACoD with MGW and fungal pretreatment can improve methane and biogas yields. First, AMoD of OFMSW was performed and compared to ACoD with MGW in terms of biogas and methane production, during this experiment different substrate to inoculum ratios (S/I) were tested using cow manure as inoculum. Later, fungal pretreatment with *P. ostreatus* and *Polyporus brumalis* was applied to ACoD mixtures prior to AD to assess its effect on biogas and methane yield. Finally, validation of different feedstock ratios during ACoD was performed. During validation, the parameter VFA/At was monitored to study possible inhibitions. The findings of the present study can be helpful for local authorities to design dry AD facilities and support decision-making processes related to waste treatment and source separation strategies.

3.2 Materials and methods

3.2.1 Source of residual waste and inoculum

The Public Services Companies of Cajicá (EPC) and Chía (EMSERCHIA), which oversee residential waste collection in the cities, provided samples of OFMSW and MGW for this study. Both municipalities gather source separated OFMSW in collection trucks. However, there are some differences among source-separation policies and collection schemes. Cajicá collects OFMSW on Mondays and Tuesdays and Chía on Wednesdays and Saturdays. Cajicá (W1) allows fruits, vegetables, eggshells, and meat residues in the organic fraction. Meanwhile, Chia (W2) only includes vegetables, fruits, eggshells, and garden waste. In both municipalities, householders collect organic fraction in open waste bins with percolate deposit at the bottom provided by the public services companies. In larger buildings, the contents of individual waste bins are compiled in an open storage bin for the whole building. For the experiments, representative samples were taken following ASTM Standard D5231-92, 2016 from residues discharged from the refuse collection vehicle. The samples were separated from the bulk using a mechanical shovel. Sub-samples of approximately 2 kg were further sorted in the laboratory to remove non-biodegradable materials and obtain an enriched organic fraction. Particle size was reduced to an average of 3-4 mm according to previous studies (Panigrahi and Dubey, 2019). Inoculum for the dry AD process was fresh cow manure collected from a nearby dairy farm and stored at 4ºC until further use. Substrates and inoculum characterization are presented in Table 3.1.

3.2.2 Physicochemical parameters

Total Kjeldahl Nitrogen (ISO 5663:1984), carbon to nitrogen ratio (ASTM: D53737), and moisture content (ASTM: D3302) were determined for substrates and inoculum. The total (TS) and volatile solids (VS) were determined by drying the samples at 105ºC for 12 h and at 550ºC for 1h until weight change was less than 50 mcg according to standard methods APHA (APHA, 1988). The pH of substrate, inoculum, and percolate were determined using a pH Checker (Hanna, United States).

Table 3. 1. Characteristics of substrates used during the present study

Parameters	W1	W2	MGW	Inoculum
pH	4.9 ± 0.2	6.2 ± 0.2	ND	7.2 ± 0.1
Moisture (%)	70.6 ± 1.27	69.1 ± 1.39	80.9 ± 1.39	ND
TS (%, w.b.)	21.60 ± 1.01	17.82± 1.03	32.34± 2.12	17.23 ± 0.05
VS (%, w.b.)	81.13± 0.04	77.34± 0.05	79.21±0.03	87.71± 0.02
C/N	17.06	23.50	23.48	24.30
Ash content (%, d.b.)	16.04± 0.2	14.79± 0.6	2.09±0.4	ND
TKN (mg N/gTS)	25.43± 1.5	11.2± 0.9	6.2± 0.2	12.7± 0.5

Note: W1, OFMSW from Cajicá; W2, OFMSW from Chía; MGW, municipal grass waste, w.b, wet base; d.b, dry base; ND; not determined, VS; volatile solids; TS, total solids; C/N, carbon to nitrogen ratio; TKN, total Kjeldahl nitrogen.
Data are mean values and standard error of three replicates.

3.2.3 Lab-scale evaluation of dry anaerobic digestion of OFMSW through different strategies

In the present section, the evaluation of biogas and methane yields during dry AD of OFMSW considering different process strategies was performed. The summary of the experiments carried out is presented in Table 3.2.

Table 3. 2. Experiments in dry AD of OFMSW

Number	Type	Substrates	Substrates ratio	Pre-treatment	Days	S/I (g VSs/gVSi)	Aim	Result
1	AMoD	W1	-	no	no	1/1, 1/2, 1/3	Evaluate the performance of mono digestion of OFMSW and its co-digestion with MGW, both locally available in Cajicá (Sabana Centro). Additionally, the effect of S/I was studied to define the best combination for the process	Best mode: mono and co-digestion; Best S/I ratio
	AMoD	W2	-	no	no	1/1, 1/2, 1/3		
	ACoD	W1-MGW	60/40	no	no	1/1, 1/2, 1/3		
	ACoD	W2-MGW	60/40	no	no	1/1, 1/2, 1/3		
2	ACoD	W1-MGW	60/40	*Pleurotus ostreatus*	7,14, 21	1/3	Evaluate the effect of a fugal pretreatment with white-rot fungi during co-digestion of OFMSW with MGW	Best pretreatment duration and fungi
	ACoD	W1-MGW	60/40	*Polyporus brumalis*	14	1/3		
3	ACoD	W1-MGW	50/50 and 70/30	no	no	1/3	Evaluate the effect of different co-digestion ratios with and without fungal pretreatment, based on the results of the previous experiments	Best co-digestion ratio, inclusion of pretreatment in process design
	ACoD	W1-MGW	50/50 and 70/30	*Pleurotus ostreatus*	7	1/3		

3.2.3.1 Anaerobic mono and co-digestion of OFMSW: effect of S/I ratio on methane yield

During the first experiment AMoD of the two different sources of OFMSW were tested and compared to ACoD with MGW in terms of biogas and methane production. ACoD was considered as a strategy to improve methane yields since it can dilute inhibitory substances, increase buffering capacity, and improve digestate characteristics for its use as agricultural fertilizer. The objective of ACoD is to balance nutrients by maintaining optimum C/N ratio

(Panigrahi and Dubey, 2019). During both AMoD and ACoD experiments, three different substrates to inoculum (S/I) ratios were evaluated: 1/1, 1/2, and 1/3 using fresh cow manure as inoculum. The S/I must be carefully selected since the inoculum provides the substrate the microorganisms and the nutrients needed for methane production. Ratios between 0.5 and 1.0 g $VS_{substrate}$/g $VS_{inoculum}$ are recommended for organic waste (Casallas-Ojeda et al., 2021). AMoD reactors were set up with only OFMSW and inoculum. and ACoD reactors with OFMSW/MGW mixtures on a 60/40 dry-weight basis and inoculum. Experiments were performed with a total mass of 250 g. The response variable was methane yield. Experiments were performed by triplicate.

Before anaerobic digestion, reactors were examined for leaks and sealed with rubber stoppers and screw caps. Dry AD was performed for45 days with a mesophilic temperature of 35 ± 1ºC. Biogas production measurements were conducted in duplicate and measured daily for the first 5 days, and every 3 days for the remaining digestion time. Methane concentration was quantified using a Claurus GC 580 (PerkinElmer, USA) equipped with a thermal conductivity detector. The temperatures of the column oven, injector port, and detector were 100, 120 and 240ºC, respectively. Argon was used as carrier gas at a flow rate of 30 mL/min. The sample volume for injection was 2 mL. Finally, biogas yields were adjusted to standard conditions using Eq.1 (Kafle and Kim, 2013).

$$V_{STP} = \frac{V_T * 273 * (760 - p_w)}{(273 + T) * 760} \tag{1}$$

Where V_{STP} is the volume of biogas at standard conditions (0ºC and 1atm) (L), V_T is the volume measured at temperature T (L), p_w is the vapor pressure of water at temperature T (mm Hg) and T is the ambient temperature (ºC). Methane yield was obtained from biogas yield using concentrations determined by gas chromatography. All experiments were performed in duplicate. Analysis of Variances (ANOVA, $\alpha = 0.05$) was performed using Minitab Statistical Software 18.1 (Minitab, USA).

3.2.4 Fungal pretreatment of OFMSW during dry ACoD

Hydrolysis of complex organic substrates is a limiting step in AD processes. Pretreatments can accelerate hydrolysis and enhance solubilization. Fungal pretreatment was evaluated as an additional strategy to enhance methane and biogas yields obtained during ACoD of W1. The following section presents the methods followed to perform the evaluation.

3.2.4.1 Preparation of the fungal inoculum

For the present study, two types of fungi were used to pretreat ACoD mixtures. The white-rot fungi *P. ostreatus* (strain DSM 1022) and *P. Brumalis* (strain DSM 1833) were provided by the German Collection of Microorganisms and Cell Cultures (DSMZ). Both fungi were cultured in malt extract peptone agar at 28ºC for 8 days. Then, 5 media pieces of approximately 5 mm diameter with grown mycelium were placed in 50 mL Erlenmeyer containing 150 mL of malt extract peptone broth. Flasks were closed with cotton stoppers and incubated with agitation for 8 days at 28ºC and 150 rpm using an Innova 42 incubator shaker (New Brunswick Scientific, United States). After 8 days, fungus was separated from broth by centrifuging at 3000 rpm for 6 minutes (Hermle, Germany) and then resuspended in 150 mL of sterilized deionized water. This solution was used as fungal inoculum. Fungus mass contained in fungal inoculum prepared with 5 and 10 plugs were 3.25 g of *P.ostreatus* and 4.15 g of *P.brumalis.*

3.2.4.2 Effect of fungal pretreatment on dry ACoD of OFMSW

The experiment evaluated the effect of performing a fungal pretreatment of ACoD mixtures before dry AD. Mixtures of OFMSW/MGW on a 40/60 basis were pretreated according to the procedure described on Section 2.5.1. Incubation time is an important parameter for biological pretreatments since it depends on biomass composition and fungus strain (Mustafa et al., 2016). The adequate selection of incubation times is one of the main obstacles for larger scales. As a result, the experimental design for this study considered pretreatment time as a factor with three levels: 7, 14 and 21 days. During fungal pretreatment, reactors were placed horizontally to increase surface area. Controls were set up as ACoD reactors without fungal pretreatment. Cow manure was used as inoculum on a

1/3 S/I ratio and added to complete 250 g of biomass, as defined during previous experiments. All experiments were performed in triplicate. AD was carried out as described in section 2.3

3.2.5 Validation of process parameters for W1

Since methane production from W1 was challenging, a final experiment was set up to define the ACoD OFMSW/MGW ratio that improve methane yields and to monitor inhibitions by toxic compound accumulation in the reactors. Last experiment was performed with an S/I ratio of 1/3 using cow manure as inoculum. The following factors were considered: (i) ACoD with two ratio levels: 50/50 and 70/30 dry weight basis; this to explore the effect of adding more MGW to the mixtures. (ii) fungal pretreatment with two levels: no pretreatment and pretreatment of mixtures. The response variables were biogas and methane yield. For reactors considering fungal pretreatment, the experimental procedure was performed as detailed in section 2.5.1. A total mass of 460 g was placed in each reactor for the final experiment. AD was carried out as reported in section 2.3. AMoD reactors were set up as controls. Additionally, to monitor the accumulation of toxic inhibitors, samples of percolate were collected from each reactor and analyzed to determine process stability by means of the rate VFA/At (Saber et al., 2021). VFA/At represent total VFA as mg/L of CH_3COOH equivalent and alkalinity, expressed as mg/L of $CaCO_3$. A 0,1 M HCl solution was used until pH 4 for VFA and 0,1 M NaOH until pH 7 for At.

3.4 Results and discussion

3.4.1 Anaerobic mono and co-digestion of OFMSW: effect of S/I ratio on methane yield

The performance of both AMoD and ACoD was evaluated by testing different S/I ratios. Results are presented in Table 3.3. During AMoD, W1 with S/I ratios of 1/1, 1/2 and 1/3 did not produce detectable methane. For W2, the lowest biogas and methane production was found for S/I ratio of 1/1 (1 NmL/ g VS and 0 NmL/ g VS respectively), and the best performance was found for S/I ratio of 1/3, with a biogas and methane yield of 253.41 NmL/ g VS and 137.72 NmL/ g VS, respectively. During ACoD with MGW, the highest biogas and methane yields were also obtained with a S/I ratio of 1/3. For W1 biogas and methane yields were 332.75 NmL/ g VS and 179.25 NmL/ g VS respectively and for W2 711.12 NmL/ g VS and 359.13 NmL/ g VS. As a result, for both experiments, the highest methane yields were found for mixtures containing inoculum at the highest rates. This result is consistent with ratios reported by previous authors (Dastyar et al., 2021; Schievano et al., 2010).

Table 3.3. Results of the dry AMoD and ACoD of the studied OFMSW

Substrates	Substrate to inoculum ratio (S/I)	Biogas volume NmL g VS-1[b]	CH4 volume NmL / VS-1[b]	Process yield (%)
W1	1/1	0[a]	0[a]	0[a]
	1/2	0[a]	0[a]	0[a]
	1/3	0[a]	0[a]	0[a]
W2	1/1	1 ± 1	6 ± 1	<1
	1/2	125 ± 22	61 ± 4	49
	1/3	253 ± 4	137 ± 62	54
ACoD-W1	1/1	0[a]	0[a]	0[a]
	1/2	0[a]	0[a]	0[a]
	1/3	332 ± 17	179 ± 8	53
ACoD-W2	1/1	0[a]	2 ± 7	0[a]
	1/2	153 ± 9	66± 4	43
	1/3	711 ± 12	359 ± 13	55

Note: W1: OFMSW from Cajicá; W2: OMFSW from Chía; ACoD-W1: co-digestion of W1 with MGW; ACoD-W2: co-digestion of W2 with MGW

[a] The methane production of inoculum was higher than the mixtures

[b] The gas volumes were normalized at 25ºC and 1 atm.

Results of AMoD experiments presented in Table 3.3 show variations in methane yields between both samples of OFMSW W1 and W2, this can be related to the differences in chemical parameters of both samples of OFMSW. The most relevant were found in TKN and C/N ratio. An adequate C/N ratio guarantees nutrient balance for microbial growth and a stable environment, ratios around 20-30 are recommended for a successful AD process (Shi et al., 2017). W1 presented low C/N ratio and high TKN, as a result, accumulation of ammonia could be possible in AMoD reactors, leading to possible failure and ineffective methane production. Nitrogen rich substrates can be challenging when anaerobic digestion processes are carried out. Free ammonia and ammonium derived from nitrogen can cause inhibitions and digester upsets. The specific mechanisms of nitrogen compounds during AD are still not well defined, although it is known that is associated directly to degradation of proteins (Jiang et al., 2019). OFMSW contains different substances belonging to the main groups of biodegradable organic materials: proteins, carbohydrates, and lipids. Meat and cheese fraction (high protein) contains TKN of around 40.2 mg N/g TS, vegetable fraction 16.1 mg N/g TS and bread-pasta fraction around 17.5 mg N/g TS (Alibardi and Cossu, 2015). Table 3.4 presents the composition of the samples of OFMSW from both sources (W1 and W2). High nitrogen contents in W1 can be related to the presence of an important meat and cheese fraction (21% w/w), leading to ammonia accumulation in AMoD reactors and an ineffective methane production.

Table 3.4. Composition of the samples of OFMSW from Cajicá (W1) and Chía (W2)

Sample	W1 %w/w	W2 %w/w
Meat-fish-cheese	21	2
Fruit	26	31
Vegetables	35	44
Bread and pasta	2	5
Others	16	18

Note: data are reported as % on wet weight (%w/w) basis

Finally, ACoD with MGW resulted in an improved performance for both processes (W1 and W2). For W1, methane production was successful and for W2 ACoD increased methane yield on 61.8%. Different studies on dry AD evidenced that the mix of highly putrescible OFMSW with fresh materials, enhance the methane production. Schievano et al. (2010) found a methane yield of 130 NmL/g VS for a sample comparable to W2 using digested solid material from a Swiss dry AD plant on a 1/3 substrate to inoculum ratio. However, samples containing meat always presented lower or ineffective methane production. During the study, the addition of a lignocellulosic materials, such as MGW was recommended to improve methane production during thermophilic dry AD (Schievano et al., 2010). Furthermore, Brown & Li (2013) studied ACoD of OFMSW with yard waste with mass ratios of 0%, 10% and 20%. Methane yields increased when OFMSW content was 10%. However, when OFMSW was increased by 20% VFA accumulation and subsequent process inhibition were found (Brown and Li, 2013). This suggested that ACoD with MGW can be beneficial, but mixture ratios must be carefully established.

Results presented in this section suggest that ACoD of OFMSW with MGW is a suitable strategy to improve methane yields during dry AD. This due to the beneficial chemical parameters of MGW. MGW has low nitrogen and protein contents, reducing the risk of ammonia accumulation during protein degradation. Additionally, dry waste such as grass are rich in carbon, their C/N ratios are greater than the optimum for AD (Rouches et al., 2016), improving the C/N ratio of both W1 and W2 ACoD mixtures.

3.4.2 Fungal pretreatment of OFMSW during dry ACoD

Due to the difficulties of methane production with W1 waste, fungal pretreatment was proposed as an additional strategy to improve methane yields. Results for ACoD of pretreated mixtures with *P.ostreatus* and *P.brumalis* are presented in Figure 3.1.

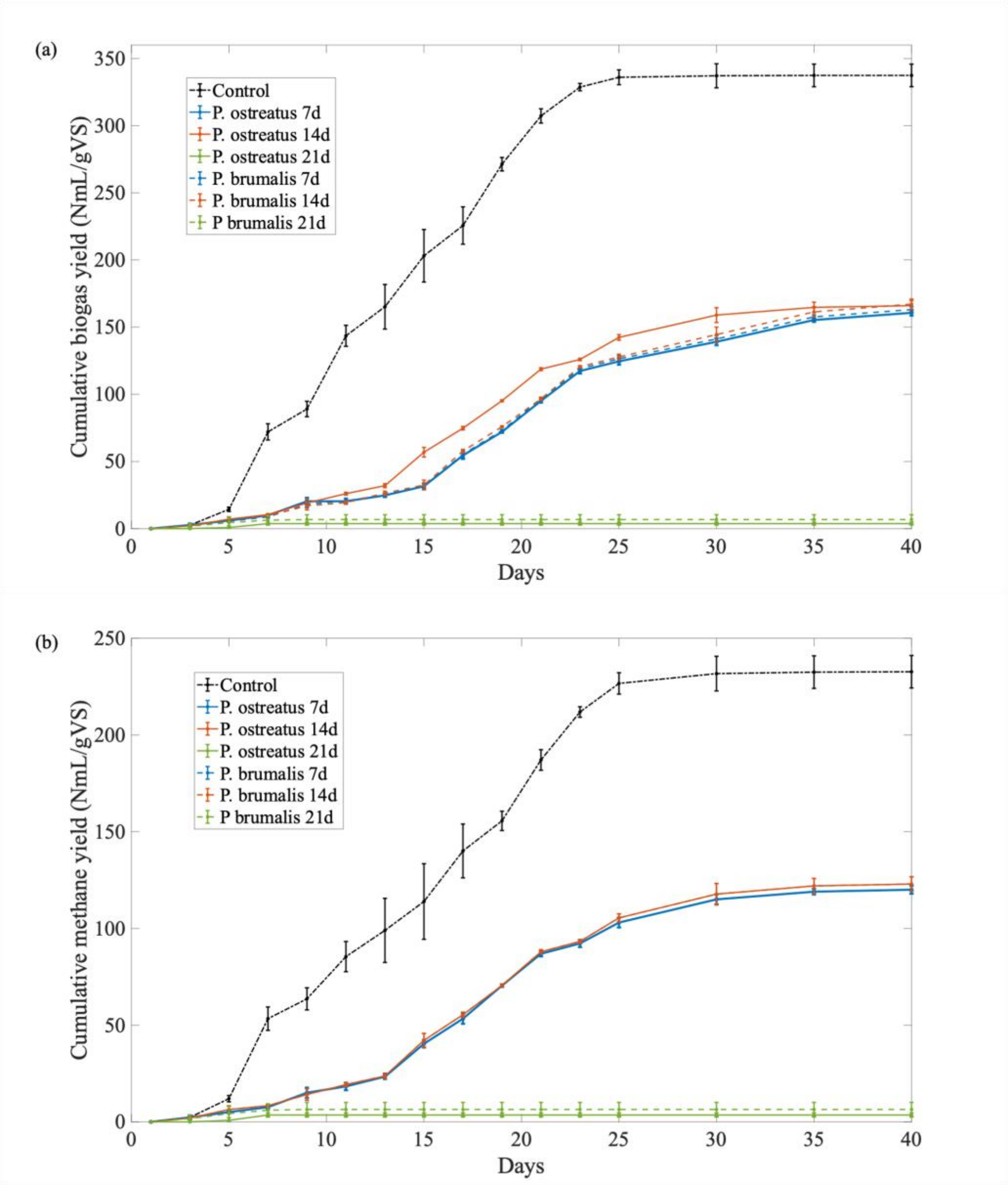


Figure 3. 1. Cumulative (a) biogas and (b) methane yield during dry AD of W1 pretreated with P.ostreatus and P.brumalis for 7, 14 and 21 days.

Biogas yields were higher when the mixture was pretreated with *P.brumalis* for 7 days (157.59 NmL/ g VS). However, the best methane yield was found for the mixture without pretreatment (224.32 NmL/ g VS), followed by the mixture pretreated with *P.brumalis* for 7 days (106.72 NmL/g VS). On the other hand, pretreatment with *P. ostreatus* did not increase neither biogas nor methane yield compared to ACoD rectors without pretreatment with a significance level of $\alpha = 0.05$. Pretreatment for 14 days resulted on a lower biogas and methane yield when compared to 7 days, and lastly when the mixture was pretreated for 21 days, biogas and methane production were the lowest. Both fungi present the same behavior in all the performed experiments (significance level of $\alpha = 0.05$). However, *P.brumalis* presented a slightly higher performance when compared to *P.ostreatus*, hence it was selected to perform pretreatments during the final experiments.

There are few studies that propose WRF to improve biogas and methane yields (Mustafa et al., 2016; Rouches et al., 2019). An average increase of 50% is reported with the pretreatment of substrates with WRF, due to an increased anaerobic degradability of substrates (Rouches et al., 2016). Mustafa, Poulsen & Sheng (2016) evaluated fungal pretreatment of rice straw with the WRF *P.ostreatus* for 10, 20 and 30 days of pretreatment and different moisture contents. Results showed that both variables had a significant effect on the degradation of cellulose, hemicellulose, and lignin (Mustafa et al., 2016). Rouches et al. (2019) performed dry AD of biologically pretreated wheat straw with the WRF *P.brumalis* considered incubation times of 13 days. Methane production was slightly lower when fungal pretreatment was performed. Additionally, the authors suggest that fungal pretreatment increased the risk of VFA accumulation (Rouches et al., 2019). Moreover, as reported by Zanellati et al. (2021), the fungus *Trichoderma longibrachiatum* increased methane yields (483.1 NmL/g VS added) when compared to controls during dry AD of rice husk. Lastly, Basinas et al. (2022) evaluated the pretreatment of corn silage with four different fungi (using *P.ostreatus*, *Dichomitus squalens*, *Trametes versicolor* and *Irpex lacteus*). *P.ostreatus* and *Dichomitus squalens* increased methane generation meanwhile *T. versicolor* and *I. lacteus* presented negative results (Basinas et al., 2022). The results presented in previous studies demonstrate that fungal pretreatment not always had a positive effect on methane yields. The possibility of accumulation of VFA was a common finding and the results of the pretreatment depended on process conditions such as substrates and the fungi used.

During the present study, results found for ACoD of W1 demonstrated that methane yields are lower when fungal pretreatment is performed. Fungal pretreatment with WRF can increase the content of nitrogen and crude proteins, modifying the amino acid composition of the initial mixtures (Rouches et al., 2016). W1 is originally high in nitrogen and proteins, as a result, fungal pretreatment resulted in a high nitrogen content of pretreated mixtures and a lower C/N ratio prior to anaerobic digestion. To explore this possibility, an additional experiment was performed adding more MGW to the final mixture.

3.4.3 Final experiment: validation of process parameters for W1

Samples of W1 were the most challenging for methane production, as a result, different feedstock ratios (OFMSW/MGW) were tested with and without fungal pretreatment to recommend the best operational parameters. Additionally, process inhibitions due to the accumulation of VFAs were studied. Cumulative biogas production for the six dry AD reactors as a function of digestion time is presented in Figure 3.2a. Biogas yield for 50/50 W1/MGW mixtures ranged from 629.32 NmL/g VS (without fungal pretreatment) to 256.89 NmL/g VS (with fungal pretreatment). For 70/30 biogas yields were lower 278.54 NmL/g VS (without pretreatment) and 138.04 NmL/g VS (with fungal pretreatment). Biogas production from the mono digestion of W1 was not successful. The best combination in terms of biogas yield was ACoD on a 50/50 dry weight basis without fungal pretreatment.

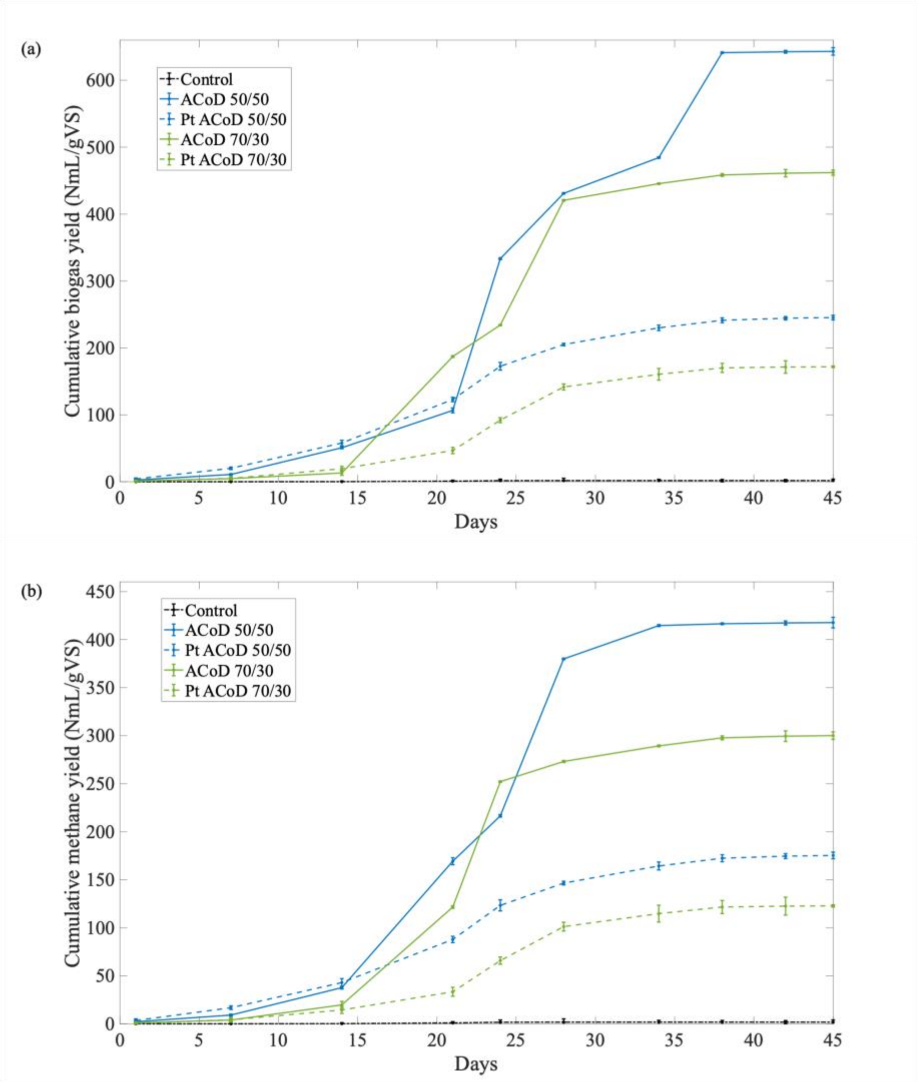
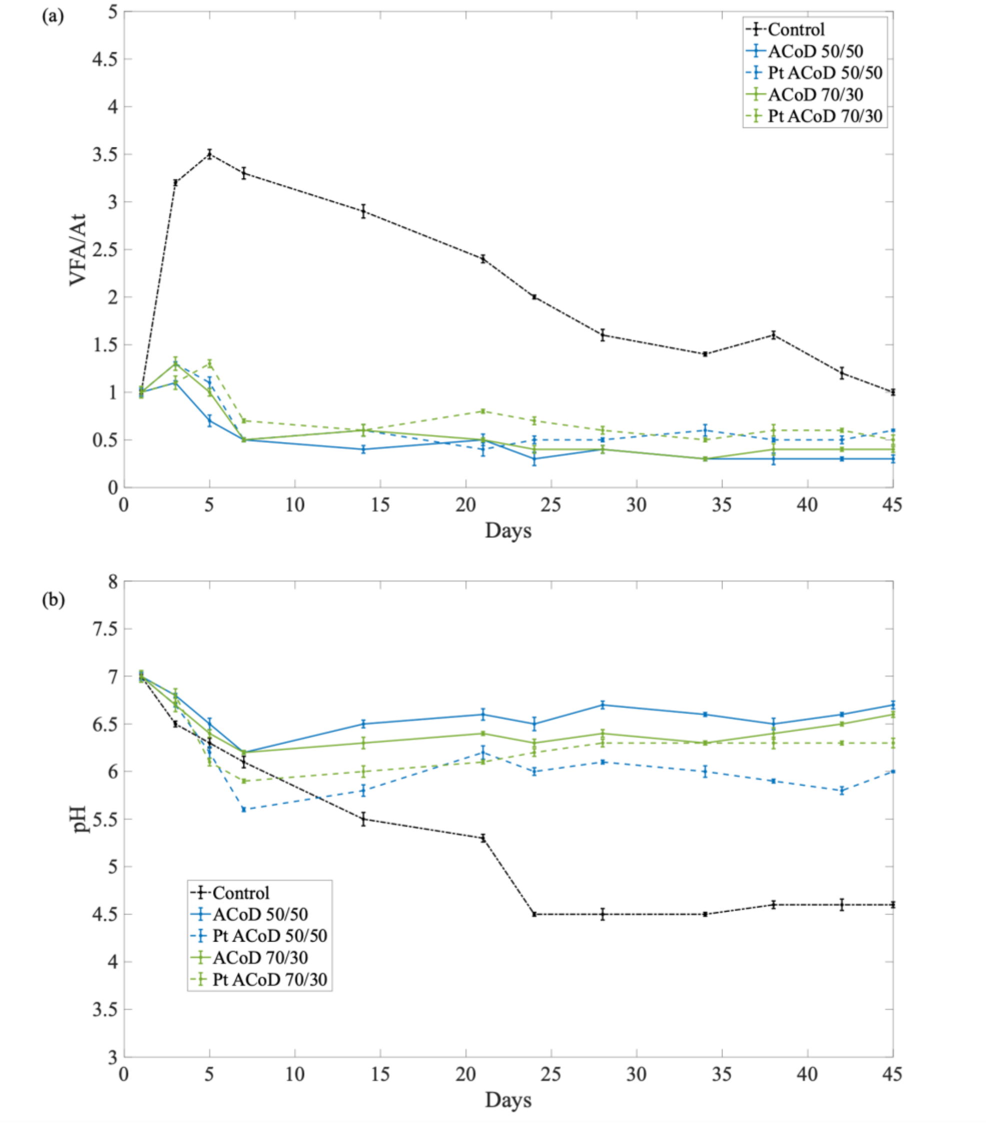


Figure 3.2. Cumulative (a) biogas and (b) methane yields during ACoD of W1 with MGW mixtures with fungal pretreatment.

Methane production as a function of time is shown in Figure 3.2b for the six combinations. Methane yields for 50/50 ACoD mixtures ranged from 417.75 NmL/g VS (without fungal pretreatment) to 157.28 NmL/g VS (fungal pretreatment), while for 70/30 mixtures from 162.99 NmL/g VS (without fungal pretreatment) to 123.01 NmL/g VS (without fungal pretreatment). Control reactors did not produce methane, proving that AMoD of W1 is ineffective.



Note: VFA, Volatile Fatty Acids; At, total alkalinity

Figure 3.3. Variation of VFA/At and pH during ACoD of OFMSW with MGW and ACoD mixtures with fungal pretreatment.

The monitoring of dry digesters is essential for stable operations and economical profitability of plants. VFA must be controlled to evaluate reactor stability. Several studies have reported that the ratio between VFA and alkalinity (VFA/At) as an efficient parameter to monitor the process (Pezzolla et al., 2017; Rouches et al., 2019; Saber et al., 2021). A ratio between 0.3 and 0.9 is recommended for the process to be stable (Lili et al., 2011; Lossie and Pütz, 2008; Rouches et al., 2019). The results of VFA/At (Figure 3.3b) showed an increase at the beginning of the process and then a gradual decrease in all tests. The acidity of percolates is expected to increase during the first stage of the digestion process due to high production of VFAs (Pezzolla et al., 2017). However, control reactors did not recover from acidification, VFA/At remain above 1 and pH (Figure 3.3b) did not increase (pH < 5.0). This is clear evidence that AMoD reactors failed due to acidification. On the other hand, reactors with 50/50 ratios showed an increase and a peak in VFA/At ratio of 1.3 by day 7 and decreased as expected, maintaining its value between 0.2 and 0.5 and its pH around 6.5. When VFAs are produced in high concentrations, methanogens cannot utilize hydrogen and VFAs as quickly as they are generated in the reactors. As a result, the process enters an inhibited steady state in which pH is relatively neutral, but methane production is not successful (Shi et al., 2017).

Commonly, the use of WRF to pretreat biomass entails a drop in pH by approximately one pH unit after five days and the possible accumulation of nitrogen in the biomass (Rouches et al., 2016). During the present study, fungal pretreatment was performed aerobically for 7 days. Aerobic degradation of organic wastes produces carbon dioxide and ammonia (Liwarska-Bizukojc and Ledakowicz, 2003). Ammonia is essential for the synthesis of amino acids and proteins and is critical for bacterial growth. However, free ammonia molecules will diffuse through cell membranes into the cells of methanogens, inhibiting methanogenesis and accumulating VFAs (Jiang et al., 2019; Shi et al., 2017). During previous studies considering biological pretreatments, methane yields of 152 L/kg VS were found when *P.ostreatus* was used to pretreat rice straw for 20 days (Mustafa et al., 2016). Wagner et al. (2013) pretreated the OFMSW with the fungi *Trichoderma viride*, increasing methane yield by 400%. However, to successfully achieve this increase, OFMSW was diluted five times, and anaerobic digestion was carried out in a liquid process (Wagner et al., 2013). On the contrary, recent studies have shown that fungal pretreatment did not always improved methane yield since the pretreatment also increased the risk of acidification (Basinas et al., 2022; Rouches et al., 2019; Zanellati et al., 2021). These results support the tendencies found during the present study. Consequently, based on these findings, the co-digestion of OFMSW containing high meat fractions with MGW is recommended at a 50/50 dry weight basis, without performing fungal pretreatment to obtain the best methane yields.

3.5 Conclusions

This study evaluated different strategies to improve methane production by dry anaerobic digestion of two different source separated OFMSW from Sabana Centro (Colombia). Methane and biogas yields were improved when ACoD was performed with OFMSW from both municipalities (W1 from Cajicá and W2 from Chia). However, methane production from W1 was challenging because it presented lower C/N ratios and higher TKN. High nitrogen concentrations in W1 reactors can be associated with high protein content of the waste associated to a large meat fraction. As a result, AMoD of W1 presented inhibitions by toxic compound accumulations, affecting methanogenic activity. According to the results, ACoD with MGW is a recommended strategy to deal with inhibitions and produce methane from OFSMW containing meat waste, as the W1 case. In addition, it is recommended for municipalities with similar meat-contained waste to increase the frequency of organics collection to avoid aerobic decomposition of waste and protein decomposition that can increase nitrogen contents in the waste. Finally, dry AD is a suitable alternative to treat different OFMSW from both municipalities in Sabana Centro when ACoD with substrates such as MGW is performed. Results of the present study can be useful for municipalities with similar source-separation policies to improve organic waste management plans and implement anaerobic digestion processes.

Acknowledgements

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References

Alibardi, L., Cossu, R., 2015. Composition variability of the organic fraction of municipal solid waste and effects on hydrogen and methane production potentials. Waste Management 36, 147–155. https://doi.org/10.1016/j.wasman.2014.11.019

André, L., Pauss, A., Ribeiro, T., 2018. Solid anaerobic digestion : State-of-art , scientific and technological hurdles. Bioresour Technol 247, 1027–1037. https://doi.org/10.1016/j.biortech.2017.09.003

APHA, 1988. Standard Methods for the Examination of Water and Wastewater, 20th ed. ed. American Water Works Association and Water Environment Federation, Washington, USA.

Basinas, P., Rusín, J., Chamrádová, K., Malachová, K., Rybková, Z., Novotný, Č., 2022. Fungal pretreatment parameters for improving methane generation from anaerobic digestion of corn silage. Bioresour Technol 345. https://doi.org/10.1016/j.biortech.2021.126526

Bedoić, R., Čuček, L., Ćosić, B., Krajnc, D., Smoljanić, G., Kravanja, Z., Ljubas, D., Pukšec, T., Duić, N., 2019. Green biomass to biogas – A study on anaerobic digestion of residue grass. J Clean Prod 213, 700–709. https://doi.org/10.1016/j.jclepro.2018.12.224

Bouaita, R., Derbal, K., Panico, A., Iasimone, F., Pontoni, L., Fabbricino, M., Pirozzi, F., 2022. Methane production from anaerobic co-digestion of orange peel waste and organic fraction of municipal solid waste in batch and semi-continuous reactors. Biomass Bioenergy 160. https://doi.org/10.1016/j.biombioe.2022.106421

Brown, D., Li, Y., 2013. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. Bioresour Technol 127, 275–280. https://doi.org/10.1016/j.biortech.2012.09.081

Casallas-Ojeda, M.R., Marmolejo-Rebellón, L.F., Torres-Lozada, P., 2021. Identification of Factors and Variables that Influence the Anaerobic Digestion of Municipal Biowaste and Food Waste. Waste Biomass Valorization 12, 2889–2904. https://doi.org/10.1007/s12649-020-01150-x

Danial, W.H., Mohd Taib, R., Abu Samah, M.A., Mohd Salim, R., Abdul Majid, Z., 2020. The valorization of municipal grass waste for the extraction of cellulose nanocrystals. RSC Adv 10, 42400–42407. https://doi.org/10.1039/d0ra07972c

Dastyar, W., Mohammad Mirsoleimani Azizi, S., Dhadwal, M., Ranjan Dhar, B., 2021. High-solids anaerobic digestion of organic fraction of municipal solid waste: Effects of feedstock to inoculum ratio and percolate recirculation time. Bioresour Technol 337. https://doi.org/10.1016/j.biortech.2021.125335

Fan, Y. Van, Lee, C.T., Jaromír, J.K., 2017. The Update of Anaerobic Digestion and the Environment Impact Assessments Research 57, 7–12. https://doi.org/10.3303/CET1757002

Franca, L.S., Bassin, J.P., 2020. The role of dry anaerobic digestion in the treatment of the organic fraction of municipal solid waste: A systematic review. Biomass Bioenergy 143. https://doi.org/10.1016/j.biombioe.2020.105866

Hallaji, S.M., Kuroshkarim, M., Moussavi, S.P., 2019. Enhancing methane production using anaerobic co-digestion of waste activated sludge with combined fruit waste and cheese whey. BMC Biotechnol 19, 1–10. https://doi.org/10.1186/s12896-019-0513-y

Hansen, T.L., Jansen, J. la C., Davidsson, Å., Christensen, T.H., 2007. Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. Waste Management 27, 398–405. https://doi.org/10.1016/j.wasman.2006.02.014

Jiang, Y., McAdam, E., Zhang, Y., Heaven, S., Banks, C., Longhurst, P., 2019. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. Journal of Water Process Engineering. https://doi.org/10.1016/j.jwpe.2019.100899

Kafle, G.K., Kim, S.H., 2013. Anaerobic treatment of apple waste with swine manure for biogas production: Batch and continuous operation. Appl Energy 103, 61–72. https://doi.org/10.1016/j.apenergy.2012.10.018

Kainthola, J., Kalamdhad, A.S., Goud, V. V., 2019. A review on enhanced biogas production from anaerobic digestion of lignocellulosic biomass by different enhancement techniques. Process Biochemistry 84, 81–90. https://doi.org/10.1016/j.procbio.2019.05.023

Li, Y., Chen, Y., Wu, J., 2019. Enhancement of methane production in anaerobic digestion process: A review. Appl Energy 240, 120–137. https://doi.org/10.1016/j.apenergy.2019.01.243

Lili, M., Biró, G., Sulyok, E., Petis, M., Borbély, J., Tamás, J., 2011. NOVEL APPROACH ON THE BASIS OF FOS/TAC METHOD, Fascicula Protecia Mediului.

Liwarska-Bizukojc, E., Ledakowicz, S., 2003. Stoichiometry of the aerobic biodegradation of the organic fraction of municipal solid waste (MSW).

Lossie, U., Pütz, P., 2008. Targeted control of biogas plants with the help of FOS/TAC: reliable assesment of the fermentation process.

Mayer, F., Bhandari, R., Gäth, S., 2019. Science of the Total Environment Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies 672, 708–721. https://doi.org/10.1016/j.scitotenv.2019.03.449

Mustafa, A.M., Poulsen, T.G., Sheng, K., 2016. Fungal pretreatment of rice straw with Pleurotus ostreatus and Trichoderma reesei to enhance methane production under solid-state anaerobic digestion. Appl Energy 180, 661–671. https://doi.org/10.1016/j.apenergy.2016.07.135

Nasir, Z., Ahring, B.K., Uellendahl, H., 2020. Enhancing the hydrolysis process in a dry anaerobic digestion process for the organic fraction of municipal solid waste. Bioresour Technol Rep 11. https://doi.org/10.1016/j.biteb.2020.100542

Ning, Z., Ji, J., He, Y., Huang, Y., Liu, G., Chen, C., 2016. Effect of Lipase Hydrolysis on Biomethane Production from Swine Slaughterhouse Waste in China. Energy & Fuels 30, 7326–7330. https://doi.org/10.1021/acs.energyfuels.6b01097

Panigrahi, S., Dubey, B.K., 2019. A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew Energy 143, 779–797. https://doi.org/10.1016/j.renene.2019.05.040

Pezzolla, D., Di Maria, F., Zadra, C., Massaccesi, L., Sordi, A., Gigliotti, G., 2017. Optimization of solid-state anaerobic digestion through the percolate recirculation. Biomass Bioenergy 96, 112–118. https://doi.org/10.1016/j.biombioe.2016.11.012

Rouches, E., Escudié, R., Latrille, E., Carrère, H., 2019. Solid-state anaerobic digestion of wheat straw: Impact of S/I ratio and pilot-scale fungal pretreatment. Waste Management 85, 464–476. https://doi.org/10.1016/j.wasman.2019.01.006

Rouches, E., Herpoël-Gimbert, I., Steyer, J.P., Carrere, H., 2016. Improvement of anaerobic degradation by white-rot fungi pretreatment of lignocellulosic biomass: A review. Renewable and Sustainable Energy Reviews 59, 179–198. https://doi.org/10.1016/j.rser.2015.12.317

Saber, M., Khitous, M., Kadir, L., Abada, S., Tirichine, N., Moussi, K., Saidi, A., Akbi, A., Aziza, M., 2021. Enhancement of organic household waste anaerobic digestion performances in a thermophilic pilot digester. Biomass Bioenergy 144, 105933. https://doi.org/10.1016/j.biombioe.2020.105933

Schievano, A., D'Imporzano, G., Malagutti, L., Fragali, E., Ruboni, G., Adani, F., 2010. Evaluating inhibition conditions in high-solids anaerobic digestion of organic fraction of municipal solid waste. Bioresour Technol 101, 5728–5732. https://doi.org/10.1016/j.biortech.2010.02.032

Shi, X., Lin, J., Zuo, J., Li, P., Li, X., Guo, X., 2017. Effects of free ammonia on volatile fatty acid accumulation and process performance in the anaerobic digestion of two typical bio-wastes. J Environ Sci (China) 55, 49–57. https://doi.org/10.1016/j.jes.2016.07.006

Silva-Martínez, R.D., Sanches-Pereira, A., Ortiz, W., Gómez Galindo, M.F., Coelho, S.T., 2020. The state-of-the-art of organic waste to energy in Latin America and the Caribbean: Challenges and opportunities. Renew Energy 156, 509–525. https://doi.org/10.1016/j.renene.2020.04.056

Tyagi, V.K., Fdez-Güelfo, L.A., Zhou, Y., Álvarez-Gallego, C.J., Garcia, L.I.R., Ng, W.J., 2018. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2018.05.051

Wagner, A.O., Schwarzenauer, T., Illmer, P., 2013. Improvement of methane generation capacity by aerobic pre-treatment of organic waste with a cellulolytic Trichoderma viride culture. J Environ Manage 129, 357–360. https://doi.org/10.1016/j.jenvman.2013.07.030

Wang, L., Shen, F., Yuan, H., Zou, D., Liu, Y., Zhu, B., Li, X., 2014. Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies. Waste Management 34, 2627–2633. https://doi.org/10.1016/j.wasman.2014.08.005

Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L., 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresour Technol 99, 7928–7940. https://doi.org/10.1016/j.biortech.2008.02.044

Zanellati, A., Spina, F., Poli, A., Rollé, L., Varese, G.C., Dinuccio, E., 2021. Fungal pretreatment of non-sterile maize silage and solid digestate with a Cephalotrichum stemonitis strain selected from agricultural biogas plants to enhance anaerobic digestion. Biomass Bioenergy 144. https://doi.org/10.1016/j.biombioe.2020.105934

Zhou, Y., Huang, K., Jiao, X., Stanisavljevic, N., Li, L., Vujovic, S., Peng, X., Wang, X., 2021. Anaerobic co-digestion of organic fractions of municipal solid waste: Synergy study of methane production and microbial community. Biomass Bioenergy 151. https://doi.org/10.1016/j.biombioe.2021.106137

Chapter 4

Process design of a dry anaerobic digestion plant for Sabana Centro, using participatory design approaches

In Chapter 2, we learnt that participatory methodologies are useful to discover hidden knowledge about a specific context. Through successful participatory approaches, we established that waste-to-energy (WtE) are promissory technologies to improve the efficiency of waste management systems. Additionally, it was also noticed that the technical feasibility of WtE technologies, especially biological treatments, depend on waste-related and demographic factors, while financial viability is based on financial resources and potential revenues considering energy and by-products. It is important to design technical processes that can meet the specific context needs. Therefore, it is necessary not only to evaluate technical feasibility of AD processes through lab and pilot-scale experiments, but also to consider specific needs in the field of implementation, including to some extent different stakeholders in the design process.

Regarding technical aspects, laboratory scale experiments performed with local OFMSW of two municipalities from Sabana Centro (Cajicá and Chía) allowed to identify relevant differences in process stability and yields (See Chapter 3). The difference in the performance of both experiments is related to variations in the initial composition and physicochemical parameters of the samples of OFMSW. These variations are linked to disparities in source-separation policies applied among municipalities of Sabana Centro, specifically between Chía and Cajicá. One of the common products inadequately disposed in municipalities such as Chía and Tabio are meat and bones. Cooked food products are not included in the organic waste that is collected in both municipalities. Keeping this in mind, pilot-scale experiments were performed using the samples with the most challenging physicochemical parameters (OFMSW from Cajicá), containing cooked food products, meat, and bones. The use of participatory approaches can help the design of processes that are appropriate for the specific characteristics of the local context.

In this chapter, an Anaerobic Digestion Participatory Methodology (ADPMDesign) is proposed to design a dry AD plant from a collective perspective, gathering and analyzing information from relevant stakeholders such as members of the municipal government, public services companies, members of the community, waste collector associations, representatives of local public services companies, researchers in anaerobic digestion, and biogas producers from dry AD plants in the UK. This chapter presents a scientific paper accepted for publication in the journal Energy for Sustainable Development. ADPMDesign is described and applied for a biogas plant to treat the OFMSW from Sabana Centro, Colombia. A combination of pilot-scale experiments, interviews, focus groups, and workshops allowed the participation of relevant stakeholders during different stages of the design process. Methodologies such as multi-criteria Analytical Hierarchy Process combined with benefit, opportunities, costs, and risk (AHP-BOCR), pilot-scale experiments, and semi-structured interviews were considered as part of ADPMDesign. Supplementary material presents process description and results of process design for the two production scenarios proposed by stakeholders from Sabana Centro. This chapter was developed as part of a project funded by the Newton Fund – Institutional links 2019 and carried out together with London Imperial College and ASOCENTRO (Asociación de Municipios de Sabana Centro) "Turning residential and industrial waste into affordable energy through dry fermentation - Sabana Centro. Colombia - Funded by Newton Fund Institutional Links".

ADPMDesign: The use of a Participatory Methodology to Design a dry anaerobic digestion power plant for municipal solid waste treatment[14]

Fabiana F. Franceschi[a], Juan Sebastián Castillo[a], Judith A. Cherni[b], Alejandro Acosta-González[c], Maria F. Gómez[d]*

Abstract

This work proposed the use of a Participatory Methodology to design a biogas-based power plant (ADPMDesign). The power plant treats the organic waste from Sabana Centro, Colombia. ADPMDesign considered the involvement of relevant stakeholders in different tasks during the design process. Stakeholders included researchers, biogas producers, members of the community, waste collector associations, representatives of local public services companies, and environmental entities. Researchers evaluated technical feasibility through pilot-scale experiments. Interviews with other stakeholders of Sabana Centro enabled the identification of two different production scenarios to forecast organic fraction of municipal solid waste generation capacity in Sabana Centro by 2030. The final use of the biogas produced during anaerobic digestion was defined through the application of a combined Analytical Hierarchy Process with Benefit Opportunity Cost and Risks in focus groups with relevant stakeholders. Then, workshops with biogas producers in the United Kingdom allowed the identification of key lessons based on their experience to improve the process design. After applying ADPMDesign, the best biogas production scenario was determined. Stakeholders in Sabana Centro, including the Municipal Government of the eleven municipalities and public service companies, should collaborate to build a single municipal plant for processing organic waste from all eleven municipalities instead of three small-scale biogas plants. This approach would not only be more efficient, but it would also facilitate better coordination and management of resources. The plant will have a capacity to treat 126.22 t/day and a power generation capacity of 3659 kW providing electricity for around 12,000 homes. The estimated cost of energy production is 78.92 COP/kWh (0.017 USD/kWh), and a payback time of 4.8 years could be achieved dispatching electricity to the national grid and selling fertilizers to local farmers.

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[14] Version accepted for publication by the journal Energy for Sustainable Development

Abbreviations – Notation

(1-T)	corporate tax rate
ACoD	anaerobic co-digestion
AD	anaerobic digestion
AMoD	anaerobic mono-digestion
AHP	analytical hierarchy process
B	biogas yield (m^3/kg)
B_i	weight of benefit i
C_i	weight of cost i
BOCR	benefits costs opportunities and risks
C_{CH_4}	volume percentage of methane
C_{CO_2}	volume percentage of carbon dioxide
C_w	volume percentage of water vapor
D	market value of debt
E	market value of equity
FOS	volatile fatty acids content
k_D	cost of debt
k_e	capital cost
KPI	key performance indicators
m_b	mas of biogas produced (kg)
m_d	mass of digestate (kg)
m_f	mass of substrates (kg)
MGW	municipal grass waste
MSW	municipal solid waste
P_i	weight of priority i
O_i	weight of opportunity i
R_i	weight of risk i
SC1	scenario 1
SC2	scenario 2
TAC	total alkalinity
TS	total solids
VFA	volatile fatty acids
VS	volatile solids
WACC	weighted average cost of capital
WtE	waste-to-energy
ρ_{CH_4}	specific weight of methane
ρ_{CO_2}	specific weight of carbon dioxide
ρ_w	specific weight of water vapor

4.1 Introduction

Nowadays, the world is facing an energy crisis. Approximately 78% of Total Energy Supply in the world is fulfilled by oil, coal, and natural gas and around 62% of electricity generation worldwide is still represented by non-renewable sources (International Energy Agency, 2020). The use of renewable sources for power generation is a new approach used to face this energy crisis (André et al., 2019) and aimed to reduce green-house gases emissions (Fernandez et al., 2018). Waste-to-energy (WtE) technologies have been under consideration during the last few decades to replace fossil fuels in the future (Panigrahi and Dubey, 2019). Biomass is currently one of the most popular alternatives among renewable energy sources. The use of biomass can reduce environmental and energy security problems issues since it represents a carbon neutral fuel (Soria et al., 2019). The successful implementation of WtE technologies depends on different factors such as waste attributes, availability, funding accessibility and environmental aspects (Chand Malav et al., 2020).

Municipal Solid Waste (MSW) generation around the world is rapidly growing, especially in developing countries mainly due to an accelerated population and economic growth. According to the World Bank, the world will generate around 1300 million tons/year of MSW by 2050 (World Bank Group, 2018). The management of large volumes of waste is still a challenge and is still not environmentally sustainable in developing countries (Cetrulo et al., 2018; Chand Malav et al., 2020). The organic fraction of municipal solid waste (OFMSW) is the largest fraction of MSW in developing countries and its inadequate disposal can contribute to various environmental problems such as climate change, ecosystem damage and resource depletion; its low heating value makes it unsuitable for thermal treatments and best for biological (Panigrahi and Dubey, 2019). Municipal Grass Waste (MGW) is part of the organic fraction and a major constituent of MSW, it has no commercial uses or industrial relevance, and its management is complex and expensive since it occupies large volumes, and it is constantly generated (Environmental Protection Agency, 2022). Nowadays, MGW is accumulated and left untreated in the field, burned, or composted. However, composting processes have presented long processing times and low product qualities due to the presence of recalcitrance components such as lignin and cellulose (Danial et al., 2020).

Anaerobic digestion is a bioprocess that has become an essential part of renewable energy since it provides both energy recovery and waste management (da Cruz Ferraz Dutra et al., 2023; Gong et al., 2020; Kesharwani and Bajpai, 2021; Qian et al., 2015). When source separation of MSW is applied AD is particularly interesting to treat its organic fraction due to the high content of volatile solids (Fantozzi and Buratti, 2011). Dry AD has multiple advantages such as decreased reactor volumes, lower energy, and water consumption, and decreased digested volumes (André et al., 2018; Jiang et al., 2018). However, due to its technical complexity dry AD is still not as popular at full scales (Kesharwani and Bajpai, 2021), there are still many challenges associated with high total solid contents such as inhibition effects, long start-up periods and low process stability (Gong et al., 2020; Ryue et al., 2020). While mono-digestion (AMoD) is the process in which a single substrate is used, in co-digestion (ACoD) two or more substrates are processed at the same time. ACoD OFMSW with complex substrates such as MGW can be a successful strategy to improve process stability and methane yields (Schievano et al., 2010). The design of dry AD municipal plants requires the knowledge of the effects produced by the composition of the substrate on biogas composition and energy balances (Scano et al., 2014).

Although technologies such as AD have an essential role in the improvement of solid waste management, in developing countries they are still not technically and financially viable due to their elevated capital investments and the lack of specific knowledge of local waste-related and demographic issues (Abdallah et al., 2020; Franceschi et al., 2022). For instance, there have been some cases in which AD processes present incompatibilities due to process designs that are not properly developed considering the specific physical characteristics of the waste (Mmereki et al., 2016). Subsequently, it would be helpful to design dry AD facilities from a collective perspective, involving different stakeholders' knowledges and skills in the designing processes (Van den Burg et al., 2016). Moreover, through the design and construction of co-digestion facilities that treat OFMSW and MGW, problems associated to their inadequate disposal can be solved, especially in developing countries.

The transition towards sustainable energy is a complex problem that involve multiple stakeholders' points of view (Guðlaugsson et al., 2020). In the field of engineering, different participatory approaches to include stakeholders have been considered to support design tasks. Stappers and Visser (2007) studied the role of participatory design techniques in industrial design engineering. Findings show that participatory design techniques are becoming an important element in new product design, including the experiences of key users in the design of a product (Stappers and Visser, 2007). Grogan (2021) studied the combination of co-design and co-simulation for engineering systems. The author concluded that co-design connected both technical integration and social negotiation perspectives relevant to attend the challenges of engineering systems of societal significance (Grogan, 2021). Lastly, the Instituto per la Ricerca Sociale is leading a project which aims to generate and disseminate knowledge on participatory governance with special focus on sustainable energy (Instituto de la Ricerca Sociale et al., 2020). The project highlights the use of participatory design approaches to design effective sustainable solutions for cities around the world. These experiences highlight the importance of include stakeholders in design activities. Additionally, different multi-criteria methods have been implemented in the formulation of policies related to waste management and the selection among treatment technologies (Lee et al., 2009). However, there are no applications of these methods to define the final product of a plant.

The use of participatory approaches in process engineering design enables the identification of factors affecting the implementation of waste-to-energy technologies and integrate them into the final design. To the author's best knowledge, there are no studies that perform a technical process design through participatory approaches. An opportunity to design AD facilities to treat municipal waste that meet local characteristics and specific needs of the end-users was identified during the present study. This study focuses on Sabana Centro, a small region of Colombia composed by eleven municipalities, since the implementation of source-separation policies to obtain the organic fraction of municipal solid waste started more than a decade ago. This is an unusual practice in Latin America and offers an opportunity to evaluate the potential of new technologies in this context. In fact, one of the municipalities separates and compost all the organic generation capacity to produce fertilizers. Moreover, there are pilot projects in some of the other municipalities to implement source-separation of organics for energy recovery. However, for this purpose, comprehensive knowledge of the context is needed. How to design a dry anaerobic digestion plant to treat the OFMSW available in Sabana Centro considering the characteristics of the local context? To address this research question, this work proposes a novel methodology (ADPMDesign) that provides a comprehensive view of the local context to facilitate the engineering design process of a dry AD plant, including relevant stakeholders in different stages of the design activities.

4.2 Materials and methods

Sabana Centro is a Colombian province founded in 1998 located in the Department of Cundinamarca (Figure 4.1), it comprises eleven municipalities: Cajicá, Chía, Cogua, Cota, Gachancipá, Nemocón, Sopó, Tabio, Tenjo, Tocancipá and Zipaquirá. The province of Sabana Centro is a region that plays an essential role in the development and growth of Bogotá (the capital of Colombia) and the Department of Cundinamarca. Moreover, national authorities support the development of infrastructure, housing, education, and health projects.

Figure 4.1. Map of the province of Sabana Centro (Cámara de Comercio de Bogotá, 2021).

There have been a few initiatives to treat the OFMSW in Sabana Centro (Pineda et al., 2015). For instance, the municipality of Cajicá is the leader of the province and the country in treating the organic fraction of waste. About 2,989 tons of waste per year are composted, representing a recycling rate of 17% for Cajicá. Composting process in Cajicá is performed by a private company and solid fertilizer is currently being used by local farmers (Hettiarachchi et al., n.d.). This success is due to a transition of more than 15 years to source separation policies that promote recycling and treating of waste. Cajicá is an example not only for the remaining ten municipalities of Sabana Centro, but also for the country. Table 4.1 presents relevant information about population, waste generation, and composting initiatives in the province of Sabana Centro.

Table 4. 1. Information about Sabana Centro (Colombia) (Sabana Centro Como Vamos, 2022)

Municipality	Population	Size (km^2)	MSW landfilled (ton/year)	Source-separation policies	Composting[a]
Gachancipá	20,150	44	3,394		
Tabio	25,172	74.5	3,393	x	x
Nemocón	15,109	94	1,761		
Cogua	25,404	136	3,645		
Tenjo	25,053	108	3,004	x	
Sopó	30,157	111.5	6,476		
Cota	38,469	55	9,936		
Tocancipá	47,539	73.51	11,789		
Zipaquirá	152,195	197	31,844	x	
Chía	155,541	76	37,306	x	x
Cajicá	96,678	51	17,988	x	x

[a] Composting is applied in Tabio and Chía at pilot scale programs and is performed by a private company in the three municipalities.

4.3 Identification and study of stakeholders

A biogas plant design must consider local agents and their needs to define final products, plant capacity, location, and even technology. Stakeholders' knowledge must not be overlooked during the design of energy systems. Participatory approaches involve relevant actors in the formulation of policies, design of public services and processes related to sustainable energy (Instituto de la Ricerca Sociale et al., 2020). The power versus interest grid is considered the best practice method for planning project stakeholder engagement (Silvius and Schipper, 2019). This method was applied to identify stakeholders' classified as "manage closely" and "keep informed". Manage closely have high influence or power and high interest in the project. Keep informed have little influence or power but high interest. Meanwhile, stakeholders classified as "keep satisfied" have high power and low interest and "monitor" have little interest and little power. Both are considered secondary stakeholders and keeping them informed about the results is enough. Classification of stakeholders for this study is presented in Figure 4.2. Stakeholders from public entities, academics, users, and experts in anaerobic digestion, must be included since they have a strong impact on energy projects.

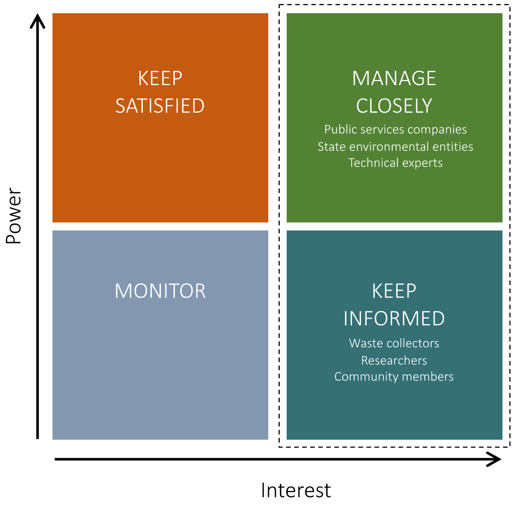

Figure 4.2. Power vs interest grid for the classification of stakeholders in waste-to-energy.

4.4 ADPMDesign: including relevant stakeholders' trough participatory approaches

During the present study, the methodology ADPMDesign was proposed and implemented to design a dry AD plant for Sabana Centro, Colombia. ADPMDesign is a strategy which encourages people that have specific knowledge about the context, and that are not necessarily trained in engineering, to work collaboratively in the design of a waste-to-energy plant. Figure 4.3 shows the different steps of the methodology, the definition and number of stakeholders included in each phase, and their individual outputs. In the following sections, an individual description for each part of the methodology is presented.

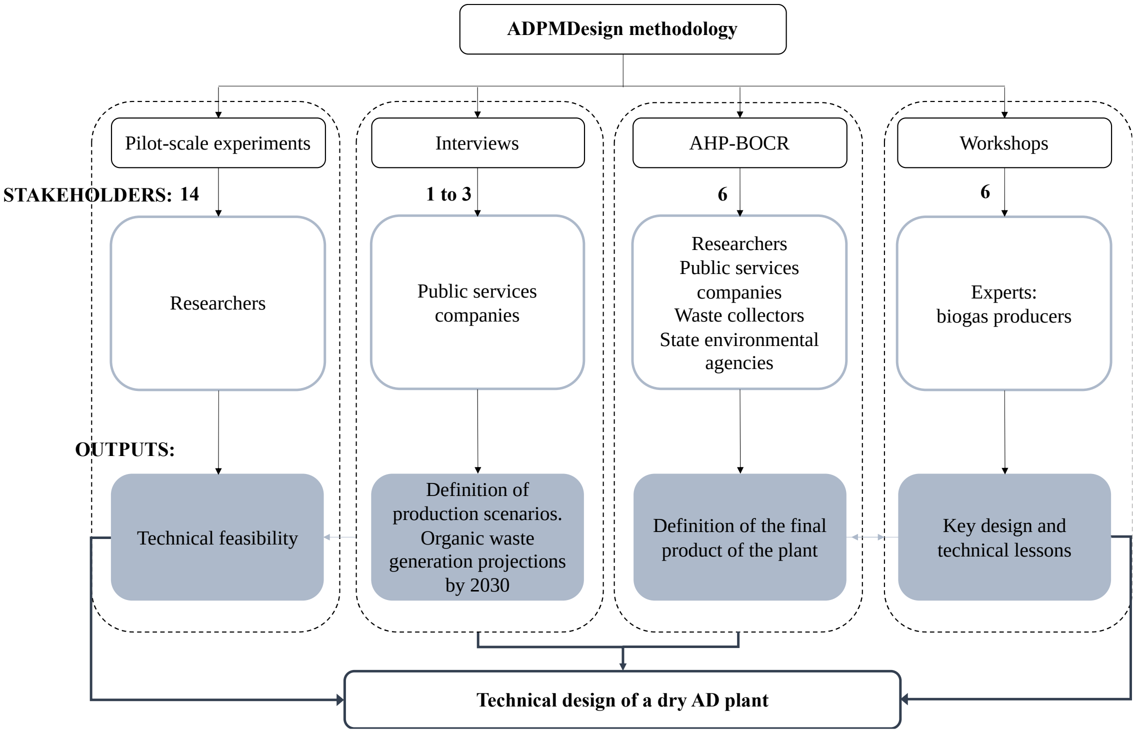

Figure 4. 3.The steps of ADPMDesign methodology

4.4.1 Pilot-scale dry anaerobic digestion: inputs from researchers

The first approach taken during ADPMDesign was to perform pilot-scale experiments to define technical feasibility of the process. The aim was to use in the experiments waste sources that are currently available in Sabana Centro. The OFMSW used for the present study was sampled twice a week and taken from the Public Services Company of Cajicá (EPC[15]) and consisted of fruit and vegetables, meat, and eggshells. Municipal Grass Waste was also obtained by the EPC and used as co-substrate. Cattle manure was used as inoculum and obtained in a slaughterhouse in Zipaquirá. For a more detailed information about substrate characterization methods and results, please refer to a previous study performed by the research team at lab-scale (Franceschi et al., 2023). Pilot-scale experiments aimed to evaluate the potential of OFMSW from Sabana Centro to produce biogas at larger scales. Cajicá was selected as a case study due to the possibility to obtain high volumes of source separated OFMSW for the experiments. Results from the experiments will be used as

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[15] In Spanish, Empresa de Servicios Públicos de Cajicá

baseline to design the power plant. Table 4.2 presents the information of the performed experiments.

Table 4.2. Pilot-scale dry AD experiments

Experiment	Feed	S/I ratio gVS [a]	T (ºC)	Waste processed (kg)
1 AMoD	OFMSW	1/3	35	681
2 ACoD	OFMSW/MGW (50/50)	1/3	35	689

[a] Substrate to inoculum ratio is presented in g of volatile solids of the substrate/ g of volatile solids of the inoculum.

The pilot-scale reactor used for the experimental design is located at the University of La Sabana in Chia, Colombia. Experiments were performed in batch mode using a 1m^3 plastic reactor (Figure 4.4). Temperature inside the reactor is controlled by a Programmable Logic Controller that (PLC) receives signals from temperature and pH sensors inside the reactor. The system controls lateral electric plates to maintain the temperature at mesophilic conditions (35°C). The reactor contains liquid sampling points to control pH and buffering capacity. Additionally, it is equipped with a percolate recirculation system with a percolate storage tank and a percolate pump to sprinkle the solid phase twice a day. Percolate recirculation pump is also driven by the controller.

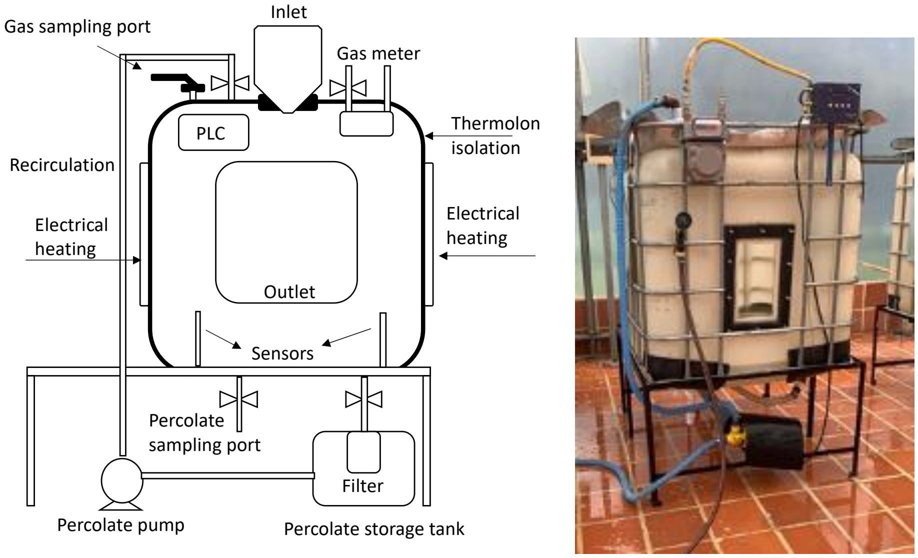

Figure 4.4. Pilot-scale 1m^3 digester used for the experimental tests.

The first experiment was the anaerobic digestion of OFMSW as a single substrate (AMoD). Then, the second experiment tested the effect of performing co-digestion with naturally dried MGW as a strategy to improve methane yields (ACoD) on a 50/50 dry weight basis. For both experiments, particle size was reduced (Panigrahi and Dubey, 2019), and the reactor was carried out in layers. For ACoD, the start-up phase lasted 9 to 12 days. Once the start-up phase was finished, process was performed by monitoring operating parameters. Biogas production was measured daily using a flowmeter (Humcar, Colombia) and methane composition was estimated daily using a portable gas analyzer GFM-406-1 (Gas Data, UK). The accumulation of toxic inhibitors was monitored by taking samples of the liquid phase to determine process stability by means of the FOS/TAC rate. FOS/TAC represent total volatile fatty acids as mg/L of CH_3COOH equivalent and alkalinity, expressed as mg/L of $CaCO_3$. For this purpose, a 0,1 M HCl solution was used until pH 4 for FOS and 0,1 M NaOH until pH 7 for TAC (Saber et al., 2021). FOS/TAC ratio is commonly used for the practical monitoring of anaerobic digestion processes, and it is an adequate indicator of buffer capacity in the digester. It is recommended FOS/TAC to be in the range of 0.3-0.4 to assure process stability (Pezzolla et al., 2017; Saber et al., 2021; Scano et al., 2014), ratios above 0.4 could be improper for the microbial population, decreasing biogas production (Scano et al., 2014).

With the parameters measured during pilot-scale experiments, mass and energy balances were developed to be used as input for process design. According to the law of conservation of mass, the mass balance for the digestion process is modeled by equation (1). The solid phase in the digester was considered the system.

$$m_f = m_d + m_b \tag{1}$$

where m_f, m_d, and m_b are the mass of substrates fed to the reactor, the mass of digestate discharged, and the mass of the biogas produced, respectively. Additionally, the mass of the biogas produced during the digestion process (m_b) must be calculated, since the quantity of gas was measured in volume. To estimate m_b, methane and carbon dioxide concentration were measured, while sulphur, and siloxanes concentrations were neglected. Concentration of water vapor was assumed to be 5% (Al Mamun and Torii, 2017).

$$m_b = B * \left[(\rho_{CH_4} * C_{CH_4}) + (\rho_{CO_2} * C_{CO_2}) + (\rho_w * C_w)\right] \tag{2}$$

where B is the biogas yield, ρ_{CH_4} is the specific weight, C_{CH_4} is the volume percentage of methane, ρ_{CO_2} is the specific weight of carbon dioxide, C_{CO_2} is the volume percentage of carbon dioxide, ρ_w is the specific weight of water vapor and C_w is the volume percentage of water vapor.

4.4.2 Interviews with public services companies: plant capacity and potential scenarios

Interviews are a fundamental part of ADPMDesign. Interviews were designed to gain knowledge about organic waste management related issues such as production of waste in Sabana Centro, current organic waste treatment, possible treatment technologies to be implemented by 2030, and the perception of stakeholders about the construction of AD plant in the province. The interviews were performed through a dialog with waste management entities following a topic guide based semi-structured lines of questioning. Ten out of the eleven municipalities and representatives of ASOCENTRO[16], participated in the interviews. Meetings that lasted around 60 minutes and were conducted in Spanish. Information about organic waste generation and treatment obtained from the interviews

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[16] In Spanish, Asociación de Municipios de Sabana Centro

were used to decide on projections about OFMSW generation in Sabana Centro by 2030 and define the capacity of the plant. To estimate plant capacities for both scenarios, the following assumptions were made: i) eight of the eleven municipalities that are recovering organic waste at pilot stage, will have the same treatment capacity that Cajicá had by 2021, ii) The remaining two municipalities will install pilot-scale organics recovery projects by 2030, with the average generation capacity of the pilot programs existing nowadays, iii) The eleven municipalities will increase its organics generation capacity according to the population growth expected by 2030.

4.4.3 Focus groups with stakeholders: definition of the final product (electricity or biomethane)

The next step of ADPMDesign considered the application of a combined Analytical Hierarchy Process (AHP) with Benefit Opportunity Cost and Risks (BOCR) study to define the final use of the biogas through focus groups with relevant stakeholders. The best feature of AHP is that it divides complex issues into key factors and sub factors by layering and calculates the weight with pairwise comparisons (Lee et al., 2009). One of the difficulties of AHP method is the selection of criteria. To solve this issue, the concept of benefits, opportunities, costs, and risk was incorporated to facilitate the evaluation of a complex problem. The combination of AHP with the benefits (B), opportunities (O), costs (C), and risks (R) have been applied to deal with positive and negative criteria in public oriented projects. Stakeholders selected for the application of focus groups were researchers from Universidad del Rosario, Universidad de la Sabana, and the Botanical Garden of Bogotá, members of the community, members of state environmental entities, waste collector associations, and public service companies. A Microsoft Excel® tool was specifically design for the application of AHP-BOCR. The tool was easy to use, and stakeholders were shortly trained in the use of the tool. Figure 4.5 presents the steps followed to apply the combined AHP-BOCR approach in the Sabana Centro biogas power plant adapted from (Saaty, 2008).

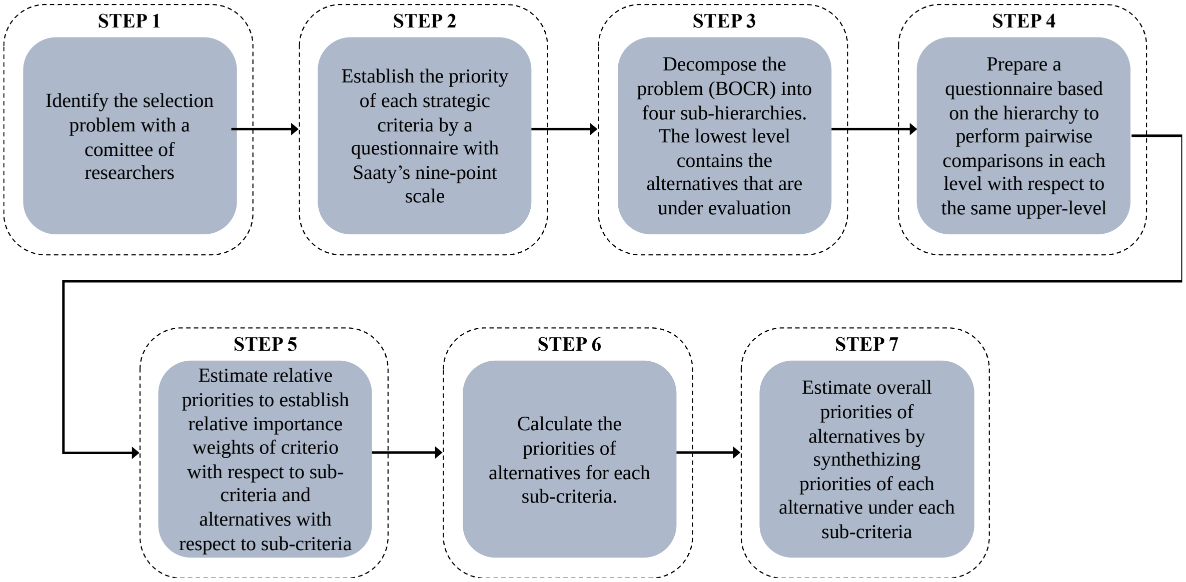

Figure 4. 5. AHP-BOCR methodology applied during focus groups.

The process started with the selection of the problem with a committee of researchers, in which the aim of the application of the method was determined as the definition of the final product. Then, the priorities of the criteria (BOCR) were established by researchers through pairwise comparison using Satty's nine-point scale. Next, BOCR were decomposed into four sub-hierarchies (Table 4.3) based on literature review and the opinion of researchers in the field, the lowest level are the alternatives (biogas for electricity, for cooking or transportation).

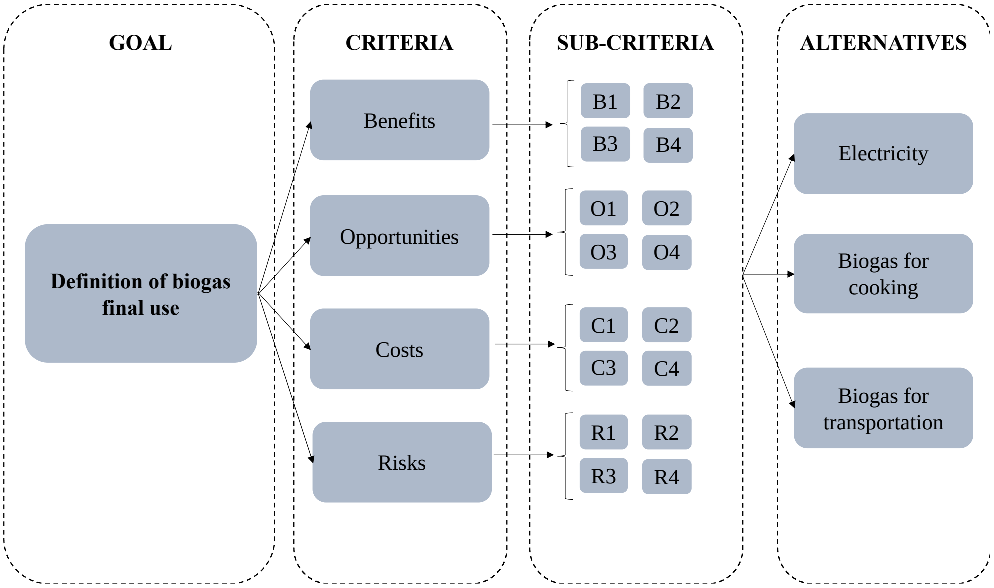

Figure 4. 6. The combined AHP with BOCR applied as part of the ADPMDesign methodology.

A questionnaire was prepared based on the hierarchies established to pairwise compare elements, in each level with respect to the same upper-level element. Stakeholders were asked to fill the questionnaire. Relative priorities were calculated in each sub-hierarchy by determining the relative importance weights of sub-criteria with respect to criteria and of alternatives with respect to sub-criteria (Figure 4.6). Finally, the priorities of alternatives for each sub-criteria were determined by synthesizing the relative importance weights. The overall priorities were determined by the arrangement of priorities of each alternative under each sub-criteria by multiplicative way:

$$P_i = B_i O_i / C_i R_i \tag{3}$$

Where Pi are the weights of each priority, Bi, Oi, Ci, and Ri are the synthesized results of alternative i under merit B, O, C and R.

Table 4. 3. Sub-criteria defined as part of the combined AHP-BOCR analysis.

BOCR Group	Sub criteria
Benefits (B)	B1. Environmental improvements
	B2. Reduction in cost of energy
	B3. Compatibility of OFMSW
	B4. Fertilizer production
Opportunities (O)	O1. R&D funding by the government
	O2. Technical maturity
	O3. Contribution to Sustainable Development Goals
	O4. Waste collector involvement in waste separation process
Costs (C)	C1. Initial investment
	C2. Operation and maintenance cost
	C3. Education programs in source-separation costs
	C4. Grid connection costs
Risks (R)	R1. Community resistance to change
	R2. Non-compliance with the separation policies
	R3. Land occupation
	R4. Changes of government
	R5. Exclusion of waste collectors in the process

Results of the focus groups acknowledge the final use of the biogas that will be produced (electricity, cooking, or transportation) according to the stakeholders' points of view and needs. The results from focus groups are an input for technical design of the plant, since the treatment technologies of biogas vary depending on its final use.

4.4.4 Experiences from biogas producers: workshops

Nowadays, the lack of knowledge about dry AD operation at higher scales compared to wet AD and the difficulties to achieve stable production makes dry AD still unpopular. However, there has been an increase of 50% in dry AD capacity in Europe from 2010 to 2015, and a global increase in popularity in the recent years due to clear advantages in terms of process flexibility and reduced need of water addition (Rocamora et al., 2020). In the UK, there are a few dry AD municipal plants treating OFMSW. During the present study, two technical visits to biogas producers in the UK were planned. Allerton Waste Recovery Park in North Yorkshire, England and Cireco Dry Anaerobic Digestion facility in Dunfermline, Scotland. The main difference between the plants is the reactor operation mode, Allerton has a continuous reactor and Cireco batch reactors. During the workshops, two different activities were performed. First, semi-structured interviews were applied to process managers during technical visits to gain perspective about process design and operation. Interviews were recorded for research purposes. Then, technical visits to the plant were carried out in which a complete perspective and knowledge of the process was gained. Both activities allowed the authors to identify key lessons that would be useful in the design for Sabana Centro.

4.4.5 Proposal of a dry anaerobic digestion plant for Sabana Centro

Once the relevant inputs were gathered through ADPMDesign, the proposal of the dry AD plant was carried out. Process engineering design was performed by a group of researchers from Universidad de La Sabana. The operating conditions chosen for the design of biogas plants were selected based on the results of pilot-scale experiments. A 20 MJ per m^3 content was considered for biogas and an electrical conversion efficiency of 35% was assumed (Ammenberg and Gustafsson, 2021). Finally, a preliminary financial evaluation was developed by a team of researchers from Universidad de La Sabana and a private company (Connect Bogotá). Mass and energy balances from process design allowed the estimation of the cost of investment. Then, Key Performance Indicators (KPI) for this project were estimated and compared with renewable energy projects in Colombia, such as biomass, photovoltaic, and hydropower (Unidad de Planeación Minero-Energética, 2021). A preliminary financial viability analysis included the following criteria (Connect Bogotá Región, 2021):

- Unit price of energy was established according to contracts with regulated and non-regulated users (200-210 COP/kWh or 0.03 EUR/kWh).
- Cost of investments considered property and equipment, construction, land, and indirect costs. Indirect costs were calculated as 19.5% of construction and land according to national indicators (Unidad de Planeación Minero-Energética, 2021).
- Operational costs such as environmental management, insurances and taxes, and operations and maintenance were considered according to national indicators (Unidad de Planeación Minero-Energética, 2021).

- WACC (Weighted Average Cost of Capital) was estimated according to Equation 4 (Connect Bogotá Región, 2021):

$$WACC = k_e \, x \, \frac{E}{E+D} + k_D(1-T) \, x \, \frac{D}{E+D} \tag{4}$$

  Where k_E is the capital cost, k_D is the cost of debt, (1-T) is the corporate tax rate, D is the market value of debt, and E is the market value of equity.
- Industry standards for negotiations of royalties in the energy sector were considered (Kapitsa and Aralova, 2015).

Finally, the payback period of the biogas power plant proposal was determined using a cash flow analysis.

4.5 Results and discussion: process design through participatory approaches

4.5.1 Technical feasibility: pilot-scale experiments

Figure 4.7 summarizes the main experimental results of the study. Biogas and methane production failed when AMoD of OFMSW was performed. When the substrate was co-digested with MGW, stability of the process was improved, with a biogas and methane production of 398.72 Nm^3/ t VS and 189.83 Nm^3/ t VS respectively. During both pilot-scale experiments, reactor stability was monitored by continuously measuring FOS/TAC parameter. For AMoD, FOS/TAC rate was 1.05 during acidification phase and decreased to 0.96. AMoD reactors presented accumulation of volatile fatty acids due to high nitrogen contents of OFMSW, possible inhibitions can be related to free ammonia and ammonium production (Jiang et al., 2019). Beneficial parameters of MGW such as low nitrogen and protein contents, and high carbon contents reduce the risk of ammonia accumulation during protein degradation improving process stability (Rouches et al., 2016). FOS/TAC ratio for ACoD experiment ranged from 0.3 to 0.6 and pH in the reactor was never lower than 5.5 demonstrating the good buffering capacity and process stability. The complete ACoD process lasted 45 days. The results found during the present study for ACoD are consistent with methane and biogas yields reported in previous studies at pilot-scales (Holtman et al., 2017; Stan et al., 2018). Additionally, pilot-scale experiments allowed to corroborate the behavior of AMoD and ACoD of the samples of OFMSW at lab-scales during a previous study (Franceschi et al., 2023).

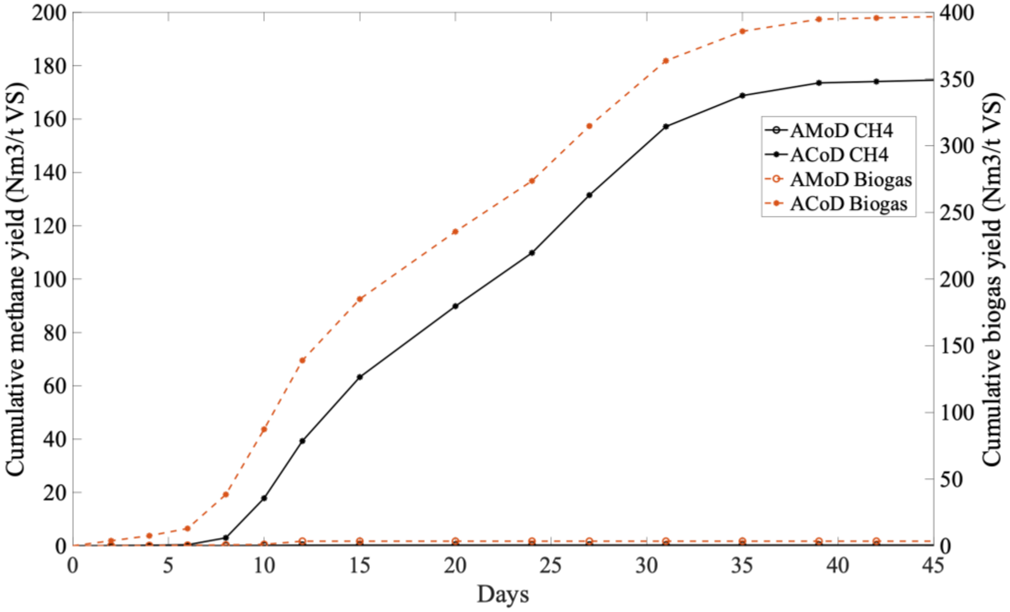

Figure 4. 7. Biogas and methane yield for the pilot-scale AMoD and ACoD of OFMSW.

During pilot-scale dry AD, 115 kg of OFMSW and 163 kg of MGW were treated for 45 days using 535 kg of fresh cow manure as inoculum. During the experiment, a total mass of 318 kg of waste was fed to the dry AD batch digester, average TS of feedstock was 19.23%, with a VS content of 83.4%. A cumulative biogas production during 45 days of operation was 210 kg containing 53% volume of methane. Total mass of digestate was 366 kg, and it was composed by 109.8 kg of liquid and 256.2 kg of solid phase. During batch operations, 23.02 kg of percolate were recirculated daily. Percolate recirculation was performed two times a day during the first 15 days and once a day until day 30.

4.5.2 Definition of production scenarios and plant capacities

First, projections of organic waste generation in the eleven municipalities were made based on the results of the interviews (Table 4.4). Only eight out of the eleven municipalities are currently collecting source separated OFMSW to some extent. However, most of them only include small areas or pilot scale projects. The leader of organics collection and treatment is

Cajicá, treating around 532 tons of OFMSW in a composting facility to produce fertilizers. This is the case of municipalities that have implemented pilot scale projects, such as Chía, Nemocón, and Tocancipá. Municipalities are applying composting due to the technical simplicity of the process. However, there is a common interest in recovering energy from waste. This interest is aligned with national policies to reduce GHG emissions and increase the share of renewable energy in the energy matrix, which also corresponds to the global interest. Additionally, findings suggested that it would be beneficial to evaluate two different production scenarios to recommend the most suitable in terms of financial feasibility: i) scenario 1 (SC1) one municipal plant to treat waste from the eleven municipalities and ii) scenario 2 (SC2) the clustering of municipalities to build multiple smaller biogas plants with the same capacity.

Table 4. 4. Organics generation projection for Sabana Centro by 2030

Municipality	Organics to compost 2030 (tons/year)	Clusters for SC2	Cluster capacity for SC2
Cajicá	6384	1	1055
Chía	10041.93		
Cota	2606.57		
Tocancipá	2941.41	2	1052
Sopó	1676.97		
Tabio	385.44		
Tenjo	1224.62		
Zipaquirá	7961.82	3	837
Gachancipá	355.58		
Nemocón	817.89		
Cogua	906.92		

Plant capacities of both scenarios were defined based on OFMSW generation projections for 2030, obtained by the interviews. For the first scenario (SC1), the eleven municipalities will deliver source separated OFMSW by collection trucks. The capacity of the plant will be 3795.68 tons of OFMSW per month and 3567.93 tons of MGW per month. The second scenario (SC2) considered the construction of three identical municipal plants with the same capacity, based on the clustering of municipalities: i) cluster one is composed by Cajicá, Chía, and Cota, ii) cluster two by Tocancipá, Sopó, Tabio, and Tenjo, and iii) cluster three by Zipaquirá, Gachancipá, Nemocón, and Cogua. The three plants will have the same capacity 1339.11 tons of OFMSW per month and 1258.76 tons of MGW per month.

4.5.3 Definition of the final product of the plant according to stakeholders' needs

The final product of the plant was defined according to the results of focus groups. In Sabana Centro, there are three possibilities: electricity, biogas for cooking, and biogas for transportation. According to the results of focus groups, around 98% of the population of Sabana Centro have access to electricity. However, there is an interest from municipalities to increase the share of renewable electricity in the matrix. Local authorities from Sabana Centro find difficulties in the use of biomethane in vehicles due to the lack of municipal budget to buy appropriate vehicles. Additionally, a lack of knowledge among stakeholders' from Sabana Centro was identified about the technical requirements that will be needed to use biomethane for cooking directly in homes. Through the application of a combined AHP-BOCR a need to produce renewable electricity from biogas in Sabana Centro was identified. Among the alternatives (electricity, biomethane for cooking and for transportation), 38% of experts, 39% of decision makers, and 50% of inhabitants chose electricity as the final product.

4.5.4 Design of the dry anaerobic digestion plant for Sabana Centro

The application of the participatory approaches allowed to design a dry AD plant to transform OFMSW from Sabana Centro. Key design lessons identified during workshops with biogas producers from the UK facilitated the refinement of the process design. The technical proposal is presented in Figure 4.8 and the detailed design basis, Process Description, and Process Flow Diagram are presented in Supplementary Material B. The process starts with the screening of the substrates to identify possible elements that can be adverse for the correct operations of dry AD. Then, substrates are sent to manual sorting, to separate recyclables and other elements that could affect anaerobic digestion performance. Later, organics are stored until the volume of waste required is gathered and sent to anaerobic digestion reactors. Dry AD process is carried out in batch mode at mesophilic conditions (35ºC) and lasts 35 to 45 days. To ensure biogas and methane productivity, the feeding of reactors requires the extraction of partially fermented material within the chamber. A portion of extracted biomass is used as inoculum. sent to the storage bay and mixed with fresh substrates in an approximate ratio of 45/55 using a front loader. This ratio may be adjusted to accommodate possible variations in the substrate composition. During dry AD, percolate is recirculated to maintain methanogenic activity inside the reactors and avoid the accumulation of VFAs. After digestion, excess percolate is sent to the effluent treatment plant. Solid digestate is sent to compost reactors for stabilization at 55ºC for 15 days. The EPA requires composting material to maintain temperature of 55ºC for 5 consecutive days or at least 15 days (Tampio et al., 2016). Stabilized digestate is stored and shredded prior to its commercialization.

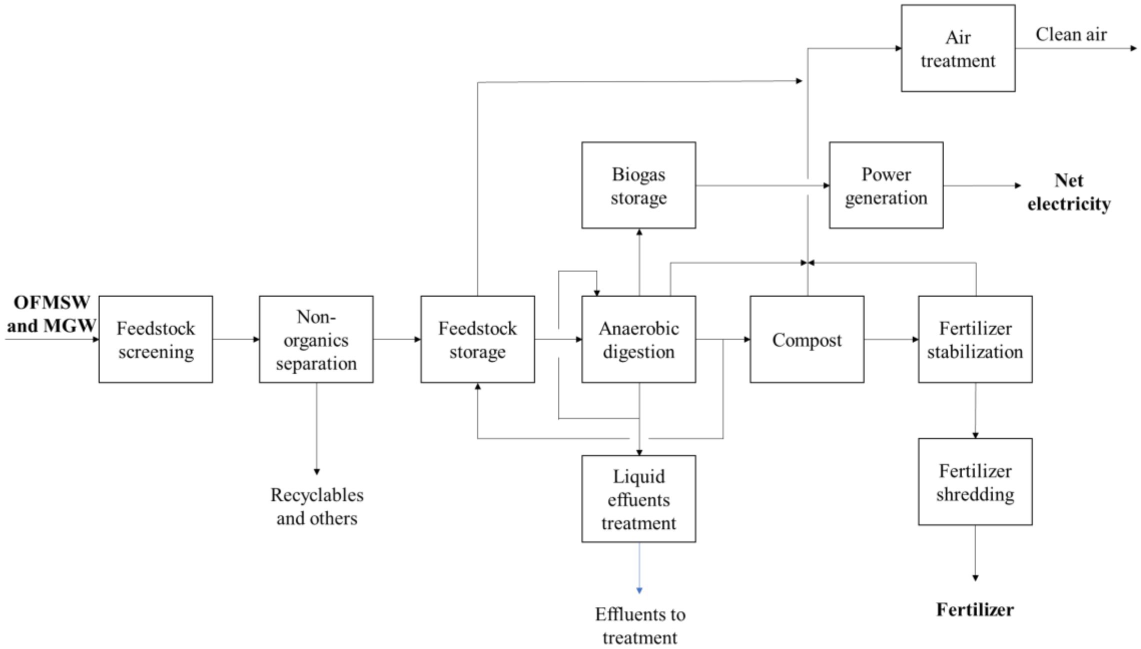

Figure 4. 8. Process diagram of the biogas power plant for Sabana Centro.

Biogas is produced in batch reactors and then stored in a storage tank. One of the main uses of biogas from waste is to produce electricity in a Combined Heat and Power plant or in a combustion engine. The utilization of biogas in these process configurations is determined by its contents of acid gases such as hydrogen sulfide (H_2S). Acidification of engine oils and corrosion of gas lines can occur if H_2S are higher than 1,000 ppm. The contents of acid gases in the biogas produced during the experiments were always lower than 1,000 pm (around 210 ppm), as a result, no biogas cleaning process is rigorously required. Therefore, biogas is filtered for odor control and then sent to a gas engine to produce electricity. While the power generation process remains the same for both scenarios, the equipment size will differ. The municipal plant for SC1 will have a capacity to process 126.22 tons of OFMSW per day, a power generation of 3,659 kW, and will have six dry anaerobic digesters of 1080 m^3 each. The second scenario involves the construction of three smaller plants near Cajicá, Chía, and Zipaquirá, each projected to have a daily capacity of 44.63 tons of OFMSW, with three 920 m3 batch digesters and a power generation capacity of 1429 kW. The construction of a dry AD power plant in Sabana Centro will provide electricity for around 12,000 homes. The main features and performance parameters of the full-scale plant for SC1 and SC2 for one cluster, are presented in Table 4.5

Table 4. 5. Performance of the power plant for both scenarios

Parameters	Scenario 1	Scenario 2
Daily OFMSW capacity (t/d)	126.22	44.63
Feedstock composition (%)	50% OFMSW/MGW w.b	
Biogas production (Nm^3/kgVS)	0.82	0.79
Methane production (Nm^3/kgVS)	0.46	0.41
Avg biogas production (Nm^3/d)	45,160	17,638
Avg methane production (Nm^3/d)	24,386	9,525
Number of digesters	6	3
Digester volume (m^3)	1080	920
Electrical efficiency	35%	35%
Engine power output (kW)	3659	1428
Gross electrical energy (kWh/d)	73560	29784
Electrical energy consumption (kWh/d)	13802	4711

Note: w.b, wet base

Investment costs for the different scenarios were calculated according to process design specifications which were obtained from the results of pilot-scale experiments. Table 4.6 shows investment costs for both scenarios in billion Colombian Pesos (COP) and USD. Considering these costs, building a municipal plant to treat organic waste from Sabana Centro is a more cost-effective alternative than constructing three smaller plants. The investment cost of a 1MW biogas power plant is usually around 4.2 to 4.8 million USD (Klimek et al., 2021). This falls within the range of costs calculated for both alternatives. KPIs are metrics that can give management visibility to the fulfillment of energy processes and objectives (Siemens Retail & Commercial Systems, 2014). Selecting appropriate KPIs for a specific project is challenging since there are multiple factors that might be considered (Faria et al., 2021). However, KPIs related to energy generation costs and productivity are generally useful (Siemens Retail & Commercial Systems, 2014). Table 4.6 presents the cost of generation in COP and USD, as well as the relationship between investment costs and installed capacity, for both scenarios. The table also includes a comparison of these costs with typical biomass, solar, and hydropower plants in Colombia (Unidad de Planeación Minero-Energética, 2021). The results suggest that Scenario 1 is more efficient than Scenario 2, based on KPIs. Moreover, typical biomass, photovoltaic, and hydropower projects are more efficient than Scenario 2. However, while a typical biomass project is more efficient than Scenario 1, the KPIs are comparable to those of a typical biomass project, and better than those of a typical solar photovoltaic project.

Table 4. 6. Key Performance Indicators for both scenarios and renewable energy projects in Colombia (Connect Bogotá Región, 2021)

KPI	Scenario 1	Scenario 2 (Per cluster)	Solar PV project	Biomass project	Hydropower project
Cost of investment (MCOP)	54,919	20,043 (total: 60,130)	-	-	-
Cost of investment (USD)	11,606,001	4,235,720 (Total: 12,707,160)	-	-	-
Installed Capacity (MWp)	3.659	1.428	20	20	820
Cost of generation (COP/kWh)	78.92	122.25	119.04	61.58	18.29
Cost of generation (USD/kWh)	0.017	0.026	0.025	0.013	0.004
Investment/installed capacity (MCOP/MWp)	10,701	19,043	15,216	9,435	8,144

[a] Costs are presented in million Colombian Pesos (COP)

To assess the financial viability of both scenarios, assumptions for financial models were made based on national indicators (Table 4.7). In Colombia, the General Royalty System (SGR[17]) was established to manage the distribution, objectives, administration, control, and use of the oil revenues. Accordingly, the SGR can finance the construction, optimization, installation, and commissioning of power generation infrastructure (UPME (Unidad de Planeación Minero Energética), 2020). As a result, Royalty discounts were taken into consideration to perform the cash flow analysis.

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[17] In Spanish, Sistema General de Regalías

Table 4. 7. Assumptions for financial models based on national indicators (Unidad de Planeación Minero-Energética, 2021)

Representative Market Rate (USD-COP)	4823
Land and construction (USD/kW)	247.50
Indirect costs (19.5% of land and construction)	48.26
Environmental management (USD/kW-year)	0.32
Insurances and taxes (USD/kW-year)	3.46
O&M + variable costs (USD/kW-year)	33.73
Royalties (%)	22.50
WACC (%)	8.1

Table 4.8 presents a summary of the results for both scenarios. If only electricity is sold to the national grid, SC1 has a payback period of around 5.8 years, while SC2 is not viable (VPN<0) under the same assumption. However, in both cases, the financial viability can be improved by commercializing the solid fertilizers produced as a by-product. SC1 has a payback period of 4.2 years, while SC2 has a payback period of 6.8 years. The results of the financial viability study indicate that SC1 is the most viable option for Sabana Centro. The municipality of Cajicá is already commercializing an organic soil amendment produced through composting and vermiculture processes. According to the information provided by the private company in charge of the composting process (IBICOL), the soil amendment is stored in bags with a capacity of 50kg and it already complies with the Resolution 068370 issued by the ICA[18] to register bioproducts for agricultural use (Instituto Colombiano Agropecuario, 2020). This fact provides a good baseline for further research. To maximize the financial potential of the project, it is beneficial that Sabana Centro invests in research on fertilizer quality and marketing strategies. Such research can help to improve the marketability of the solid fertilizers produced as a by-product, and ultimately reduce the payback period of the project even further.

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[18] In Spanish, Insituto Colombiano Agropecuario

Table 4.8. Summary of the results of the financial viability study (Connect Bogotá Región, 2021)

	Scenario 1	Scenario 2
VPN without by-products (MCOP)	66,230	-18,715
VPN without by-products (MUSD)	13.99	-3.95
Payback	5.8 years	-
VPN with by-products (MCOP)	156,051	12,448
VPN with by-products (MUSD)	32.97	2.63
Payback	4.2 years	6.8 years

According to National Order 030 of 2018, issued by the Energy and Gas Regulations Commission, electricity producers can access the national electricity markets as large-scale auto-generators when they produce less than 5 MW. The main outcome of the participatory process design is a recommendation to stakeholders in Sabana Centro and its eleven municipalities to construct a large-scale municipal biogas plant for treating organic waste generated within the region. Collaboration among the municipal authorities from the eleven municipalities to build a single large-scale biogas plant is more advantageous than constructing smaller individual plants. Moreover, it is recommended that the municipalities adopt unified source-separation policies to promote a more consistent composition of the OFMSW. This approach will not only facilitate more stable biogas production but also ensure a more uniform biogas composition.

The results of the application of ADPMDesign in Sabana Centro will be useful for stakeholders such as municipal governments, members of the environmental entities, the Public Services Companies, ASOCENTRO, and the Sabana Centro community in general. According to Connect Bogotá Región (2021) Business models can be built around the following recommendations i) sell electricity to the national grid, ii) establish collaboration agreements for co-production, joint marketing, and management, operation and maintenance processes, iii) create Joint Ventures to share resources, profits, losses, and expenses, iv) explore Public-Private Partnerships mechanisms to perform waste management related activities than can reduce the high cost and risk of investment associated to waste treatment technologies (Connect Bogotá Región, 2021)

The ADPMDesign methodology facilitated a thorough understanding of the local context's needs and characteristics, which were then incorporated as a vital component of the process design. This approach enabled the engineers to not only account for the plant's technical requirements but also anticipate and address real-world challenges that the plant may encounter. Researchers in AD can also benefit from ADPMDesign, as it can be applied in different cities in Colombia and other Latin American countries where the Municipal Government is responsible for waste management activities. Finally, through the application of ADPMDesign in Sabana Centro, some limitations were identified. The main limitation is the coordination of stakeholders' schedules to perform workshops, interviews, and focus groups. It is strongly recommended to carefully schedule stakeholders with plenty of time to avoid delays. Additionally, there are limitations related to the confidentiality of information. The information provided by the stakeholders can be used only for research purposes and by the research team. Therefore, researchers must handle information carefully.

4.5 Conclusions

The study introduces a novel methodology, ADPMDesign, which adopts a collective perspective to design a dry anaerobic digestion plant, thereby gaining a deeper understanding of the implementation context. This approach facilitates the design of a power plant to meet the specific needs of the municipality or region. ADPMDesign was applied to Sabana Centro (Colombia) with the participation of stakeholders such as researchers, private institutions, biogas producers in the UK, environmental entities and public services companies, and civil society of the municipalities. Through different approaches, the methodology obtained design inputs including mass and energy balances, key lessons, production scenarios, plant capacities, final use of the biogas, and financial viability. The methodology enabled the verification of technical feasibility by proposing the co-digestion of OFMSW with MGW to increase methane production. This was necessary as mono digestion presented inhibitions due to the accumulation of VFAs. The best alternative for Sabana Centro is to build one municipal biogas plant for power generation purposes with a capacity of 45,549 tons per year with six batch digesters of 1080 m^3 each, with a capacity of 188.99 t/day, an estimated power generation of 3659 kW, and a payback time of about 5.8 years if only electricity is sent to the national grid. Marketing fertilizers can lead to improvements in payback time (4.2 years). Therefore, it is recommended that future research includes studies to develop strategies for its commercialization. By adopting ADPMDesign, engineers were able to consider not just the technical aspects of the plant but also anticipate and proactively address specific needs of local stakeholders. Researchers in the field of AD are encouraged to use ADPMDesign in other cities in Colombia and countries in which Municipal Government is responsible for waste management activities.

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References

Abdallah, M., Arab, M., Shabib, A., El-Sherbiny, R., El-Sheltawy, S., 2020. Characterization and sustainable management strategies of municipal solid waste in Egypt. Clean Technol Environ Policy 22, 1371–1383. https://doi.org/10.1007/s10098-020-01877-0

Al Mamun, M.R., Torii, S., 2017. Enhancement of Methane Concentration by Removing Contaminants from Biogas Mixtures Using Combined Method of Absorption and Adsorption. International Journal of Chemical Engineering 2017. https://doi.org/10.1155/2017/7906859

Ammenberg, J., Gustafsson, M., 2021. Perspectives on biomethane as a transport fuel within a circular economy, energy, and environmental system Optimisation of value chains for biogas production in Denmark (Biochain) View project.

André, L., Pauss, A., Ribeiro, T., 2018. Solid anaerobic digestion : State-of-art , scientific and technological hurdles. Bioresource Technol 247, 1027–1037. https://doi.org/10.1016/j.biortech.2017.09.003

André, L., Zdanevitch, I., Pineau, C., Lencauchez, J., Damiano, A., Pauss, A., Ribeiro, T., 2019. Dry anaerobic co-digestion of roadside grass and cattle manure at a 60 L batch pilot scale. Bioresource Technol 289, 121737. https://doi.org/10.1016/j.biortech.2019.121737

Cámara de Comercio de Bogotá, 2021. Sedes y área de influencia CCB [WWW Document]. Mapa municipio de Cundinamarca. Provincia Sabana Centro v.4.

Cetrulo, T.B., Marques, R.C., Cetrulo, N.M., Pinto, F.S., Moreira, R.M., Mendizábal-Cortés, A.D., Malheiros, T.F., 2018. Effectiveness of solid waste policies in developing countries: A case study in Brazil. J Clean Prod 205, 179–187. https://doi.org/10.1016/j.jclepro.2018.09.094

Chand Malav, L., Yadav, K.K., Gupta, N., Kumar, S., Sharma, G.K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q.B., Yadav, S., Bhattacharyya, S., Yadav, V.K., Bach, Q.V., 2020. A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. J Clean Prod 277, 123227. https://doi.org/10.1016/j.jclepro.2020.123227

Connect Bogotá Región, 2021. Implementación de la tecnología de fermentación seca a partir de los residuos sólidos urbanos: Informe de Valoraciones Tecnológicas. Bogotá.

da Cruz Ferraz Dutra, J., Passos, M.F., García, G.J.Y., Gomes, R.F., Magalhães, T.A., dos Santos Freitas, A., Laguna, J.G., da Costa, F.M.R., da Silva, T.F., Rodrigues, L.S., Américo, M.F., Campos, G.M., Pereira, G., Vandenbeghe, L., Soccol, C.R., Góes-Neto, A., de Carvalho Azevedo, V.A., 2023. Anaerobic digestion using cocoa residues as substrate: Systematic review and meta-analysis. Energy for Sustainable Development 72, 265–277. https://doi.org/10.1016/j.esd.2022.12.007

Danial, W.H., Mohd Taib, R., Abu Samah, M.A., Mohd Salim, R., Abdul Majid, Z., 2020. The valorization of municipal grass waste for the extraction of cellulose nanocrystals. RSC Adv 10, 42400–42407. https://doi.org/10.1039/d0ra07972c

Enviromental Protection Agency, 2022. Yard Trimmings: Material-Specific Data [WWW Document]. Facts and Figures about Materials, Waste and Recycling.

Fantozzi, F., Buratti, C., 2011. Anaerobic digestion of mechanically treated OFMSW: Experimental data on biogas/methane production and residues characterization. Bioresource Technology 102, 8885–8892. https://doi.org/10.1016/j.biortech.2011.06.077

Faria, P., Lezama, F., Vale, Z., Khorram, M., 2021. A methodology for energy key performance indicators analysis. Energy Informatics 4. https://doi.org/10.1186/s42162-021-00140-0

Fernandez, A., Román, C., Mazza, G., Rodriguez, R., 2018. Determination of effective moisture diffusivity and thermodynamic properties variation of regional wastes under different atmospheres. Case Studies in Thermal Engineering 12, 248–257. https://doi.org/10.1016/j.csite.2018.04.015

Franceschi, F.F., Acosta-Gonzalez, A., Vega, L.T., Gomez, M.F., 2023. Improving dry anaerobic methane production from OFMSW by co-digestion with grass waste and pretreatment with white rot fungi. Manuscript Submitted for publication, Universidad de La Sabana.

Franceschi, F.F., Vega, L.T., Sanches-Pereira, A., Cherni, J.A., Gómez, M.F., 2022. A combined approach to improve municipal solid waste management in upper-middle-income countries: the case of Sabana Centro, Colombia. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-022-02333-x

Gong, H., Liu, M., Li, K., Li, C., Xu, G., Wang, K., 2020. Optimizing dry anaerobic digestion at pilot scale for start-up strategy and long-term operation: Organic loading rate, temperature and co-digestion. Bioresour Technol 316, 123828. https://doi.org/10.1016/j.biortech.2020.123828

Grogan, P.T., 2021. Co-design and co-simulation for engineering systems: Insights from the Sustainable Infrastructure Planning Game. Design Science. https://doi.org/10.1017/dsj.2021.10

Guðlaugsson, B., Fazeli, R., Gunnarsdóttir, I., Davidsdottir, B., Stefansson, G., 2020. Classification of stakeholders of sustainable energy development in Iceland: Utilizing a power-interest matrix and fuzzy logic theory. Energy for Sustainable Development 57, 168–188. https://doi.org/10.1016/j.esd.2020.06.006

Hettiarachchi, H., Caucci, S., Schwärzel, K., n.d. Organic Waste Composting through Nexus Thinking.

Holtman, K.M., Bozzi, D. V., Franqui-Villanueva, D., Offeman, R.D., Orts, W.J., 2017. Pilot scale high solids anaerobic digestion of steam autoclaved municipal solid waste (MSW) pulp. Renew Energy 113, 257–265. https://doi.org/10.1016/j.renene.2017.03.050

Instituto Colombiano Agropecuario, 2020. Resolucion 068370. Colombia.

Instituto de la Ricerca Sociale, Turin University, Milan Polytechnic, Stockholm Environment Institute Tallinn Centre, (ALDA), E.A. for L.D., 2020. Project : ENLARGE – Energies for Local Administrations to Renovate Governance in Europe.

International Energy Agency, 2020. Electricity generation by source, World 1990-2021 [WWW Document]. URL https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy supply&indicator=ElecGenByFuel (accessed 5.4.21).

Jiang, Y., Dennehy, C., Lawlor, P.G., Hu, Z., McCabe, M., Cormican, P., Zhan, X., Gardiner, G.E., 2018. Inhibition of volatile fatty acids on methane production kinetics during dry co-digestion of food waste and pig manure. Waste Management 79, 302–311. https://doi.org/10.1016/j.wasman.2018.07.049

Jiang, Y., McAdam, E., Zhang, Y., Heaven, S., Banks, C., Longhurst, P., 2019. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. Journal of Water Process Engineering. https://doi.org/10.1016/j.jwpe.2019.100899

Kapitsa, Y.U., Aralova, N., 2015. Determination of royalty rates for international technology transfer agreements. Science and Innovation 11, 51–68. https://doi.org/10.15407/scine11.02.051

Kesharwani, N., Bajpai, S., 2021. Pilot scale anaerobic co-digestion at tropical ambient temperature of India: Digester performance and techno-economic assessment. Bioresour Technol Rep 15, 100715. https://doi.org/10.1016/j.biteb.2021.100715

Klimek, K., Kapłan, M., Syrotyuk, S., Bakach, N., Kapustin, N., Konieczny, R., Dobrzyński, J., Borek, K., Anders, D., Dybek, B., Karwacka, A., Wałowski, G., 2021. Investment model of agricultural biogas plants for individual farms in Poland. Energies (Basel) 14. https://doi.org/10.3390/en14217375

Lee, A.H.I., Chen, H.H., Kang, H.Y., 2009. Multi-criteria decision making on strategic selection of wind farms. Renew Energy 34, 120–126. https://doi.org/10.1016/j.renene.2008.04.013

Mmereki, D., Baldwin, A., Li, B., 2016. A comparative analysis of solid waste management in developed, developing and lesser developed countries. Environmental Technology Reviews. https://doi.org/10.1080/21622515.2016.1259357

Panigrahi, S., Dubey, B.K., 2019. A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste. Renew Energy 143, 779–797. https://doi.org/10.1016/j.renene.2019.05.040

Pezzolla, D., Di Maria, F., Zadra, C., Massaccesi, L., Sordi, A., Gigliotti, G., 2017. Optimization of solid-state anaerobic digestion through the percolate recirculation. Biomass Bioenergy 96, 112–118. https://doi.org/10.1016/j.biombioe.2016.11.012

Pineda, N.M., Camelo, J.C., Bejarano, A.M., Castro, L.A., Vengoechea, J.R., Ortíz, J.G., 2015. Sabana Centro Cómo Vamos Informe de calidad de vida Sabana Centro Cómo Vamos Línea base 2014-2015 180.

Qian, M.Y., Li, R.H., Li, J., Wedwitschka, H., Nelles, M., Stinner, W., Zhou, H.J., 2015. Industrial scale garage-type dry fermentation of municipal solid waste to biogas. Bioresour Technol 217, 82–89. https://doi.org/10.1016/j.biortech.2016.02.076

Rocamora, I., Wagland, S.T., Villa, R., Simpson, E.W., Fernández, O., Bajón-Fernández, Y., 2020. Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. Bioresour Technol 299, 122681. https://doi.org/10.1016/j.biortech.2019.122681

Rouches, E., Herpoël-Gimbert, I., Steyer, J.P., Carrere, H., 2016. Improvement of anaerobic degradation by white-rot fungi pretreatment of lignocellulosic biomass: A review. Renewable and Sustainable Energy Reviews 59, 179–198. https://doi.org/10.1016/j.rser.2015.12.317

Ryue, J., Lin, L., Kakar, F.L., Elbeshbishy, E., Al-Mamun, A., Dhar, B.R., 2020. A critical review of conventional and emerging methods for improving process stability in thermophilic anaerobic digestion. Energy for Sustainable Development. https://doi.org/10.1016/j.esd.2019.11.001

Saaty, T.L., 2008. Decision making with the analytic hierarchy process, Int. J. Services Sciences.

Sabana Centro Como Vamos, 2022. Informe de calidad de vida 2021. Chia.

Saber, M., Khitous, M., Kadir, L., Abada, S., Tirichine, N., Moussi, K., Saidi, A., Akbi, A., Aziza, M., 2021. Enhancement of organic household waste anaerobic digestion performances in a thermophilic pilot digester. Biomass Bioenergy 144, 105933. https://doi.org/10.1016/j.biombioe.2020.105933

Scano, E.A., Asquer, C., Pistis, A., Ortu, L., Demontis, V., Cocco, D., 2014. Biogas from anaerobic digestion of fruit and vegetable wastes: Experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant. Energy Convers Manag 77, 22–30. https://doi.org/10.1016/j.enconman.2013.09.004

Schievano, A., D'Imporzano, G., Malagutti, L., Fragali, E., Ruboni, G., Adani, F., 2010. Evaluating inhibition conditions in high-solids anaerobic digestion of organic fraction of municipal solid waste. Bioresour Technol 101, 5728–5732. https://doi.org/10.1016/j.biortech.2010.02.032

Siemens Retail & Commercial Systems, 2014. Managing Energy Using Key Performance Indicators.

Silvius, Schipper, 2019. Planning Project Stakeholder Engagement from a Sustainable Development Perspective. Adm Sci 9, 46. https://doi.org/10.3390/admsci9020046

Soria, J., Li, R., Flamant, G., Mazza, G.D., 2019. Influence of pellet size on product yields and syngas composition during solar-driven high temperature fast pyrolysis of biomass. J Anal Appl Pyrolysis 140, 299–311. https://doi.org/10.1016/j.jaap.2019.04.007

Stan, C., Collaguazo, G., Streche, C., Apostol, T., Cocarta, D.M., 2018. Pilot-scale anaerobic co-digestion of the OFMSW: Improving biogas production and startup. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10061939

Stappers, P.J., Visser, F.S., 2007. Bringing participatory techniques to industrial design engineers. DS 43: Proceedings of E and PDE 2007, the 9th International Conference on Engineering and Product Design Education 117–122.

Tampio, E., Marttinen, S., Rintala, J., 2016. Liquid fertilizer products from anaerobic digestion of food waste: Mass, nutrient and energy balance of four digestate liquid treatment systems. J Clean Prod 125, 22–32. https://doi.org/10.1016/j.jclepro.2016.03.127

Unidad de Planeación Minero-Energética, 2021. Proyección Demanda Energía Eléctrica y Gas Natural 2021-2035. Bogotá, Colombia.

UPME (Unidad de Planeación Minero Energética), 2020. Plan Energético Nacional 2020-2050 2015.

Van den Burg, S., Stuiver, M., Norrman, J., Garção, R., Söderqvist, T., Röckmann, C., Schouten, J.J., Petersen, O., García, R.G., Diaz-Simal, P., Bel, M. de, Aja, L.M., Zagonari, F., Zanuttigh, B., Sarmiento, J., Giannouli, A., Koundouri, P., 2016. Participatory design of multi-use platforms at sea. Sustainability (Switzerland) 8, 1–17. https://doi.org/10.3390/su8020127

World Bank Group, 2018. What a Waste 2.0 Introduction -"Snapshot of Solid Waste Management to 2050." Overview booklet. Urban Development Series 1–38.

Supplementary material A

Semi-structured interviews format

Date:

Address:

Owned by:

Team:

Feedstocks and capacity

What is the capacity of the plant in tons/time?

How many digesters are in the plant?

What is the volume of the digester(s)?

What is the composition of the feedstock/biomass?

What is the pH of the feedstock?

Pretreatment

Do you perform a pretreatment of the feedstock?

If positive, describe the pretreatment.

Operation

Describe the startup process?

What do you use as inoculum and how is it obtained?

How often digesters are loaded and how stable biogas production is ensured?

What is the pH of the feedstock?

What are the total solids (%) of the feedstock?

Is pH adjusted during operation?

If positive, how is it adjusted?

Have inhibitions occurred during the process?

If positive, how do you deal with them?

Are the digesters(s) equipped with an internal heating system?

If positive, specify the system.

If negative, explain how the operating temperature is maintained?

How long does the stabilization phase last?

Do you perform percolate recirculation?

If positive, describe the process.

Were the digesters provided by a commercial vendor?

Please write the brand and model

Are the digesters(s) equipped with biogas filters?

If positive, describe the filtering process.

Digestate treatment

How do you process digestate?

and what quality tests are performed?

Final product

Which technology is used to treat biogas?

Which technology is used to generate electricity?

What is the power generated (kW-MW)?

Is the plant connected to the power grid?

Yes

In your opinion, why did you choose dry AD instead of wet?

What are the advantages of using dry AD in this plant?

Supplementary Material B

Process Flow Diagram and Process description for Sabana Centro SC1

It is relevant to mention that an additional pilot-scale experiment was performed at the Botanical Garden of Bogotá (JBB[19]), as part of the activities of Project I. The experiments lasted 2 years and allowed to understand the complexity of dealing with larger amounts of waste and to identify opportunities to improve the performance of the pilot plant. The dry AD plant was built by a local provider and consist of the following elements: three garage type digesters working in parallel, build in concrete with 30 cubic meters of volume each, airtight doors, underground tanks with 13.5 litters, a trap of variable granulometry ensures the screening of the solid material inside the digesters, the percolate tank with 1 cubic meter, percolate recirculation system, the biogas network, and the percolate electrical heating system. The results of this experience were presented as a short scientific article "Lessons for the design of garage type dry anaerobic digestion pilot plants: the case of the Botanical Garden of Bogotá" at the international conference BERSTIC[20] 2022. The short article is presented in Appendix V.

General design basis:

- Even though OFMSW is source separated, the presence of other materials and recyclables is frequent. Recyclables are assumed to be 5% of total waste received and others 1% of total waste received. This assumption is made based on the results found during the pilot-scale experiments performed at the JBB pilot plant, presented in Appendix V.
- Recyclables separated at the facility are collected once a week by local waste collectors for scenarios SC2 and Cajicá and once a week for SC1.
- Other waste separated at the facility are collected by local public services companies and disposed in landfills once a week for scenarios SC2 and Cajicá and once a week for SC1.

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[19] In Spanish, Jardín Botánico de Bogotá

[20] In Spanish, Biorrefinerías y Energías Renovables Soportadas en TIC

- The height of fermentation chambers/reactors is 5 m. However, the biomass must not exceed 4 m to store accumulated gases and avoid an increase in internal pressure. Hence, a biomass height of 3.5 m is recommended.
- Percolate generation rate was defined according to the results of pilot-scale experiments. In the 1m^3 reactor 1L of percolate was generated daily and in the 14 tons reactor, 1m^3 of percolate was generated daily.
- Biogas and methane yields used to perform mass and energy balances calculations were based on the results of pilot-scale experiments (389.72 Nm^3/ton VS).
- Biogas composition was established according to laboratory and pilot-scale results: 48% methane, 40% carbon dioxide, 120 ppm of hydrogen sulfide, and less than 5% of water.
- Biogas production in percolate tank is recovered and sent to reactors, biogas volume from percolate tank was estimated as 5% of the total biogas volume produced in the reactor chambers.
- Condensation of water in biogas storage tanks was estimated as 5% of total biogas volume stored.
- Warm water is used as utility for reactor in floor heating and to heat percolate in percolate tanks. Average warm water temperature is considered 85ºC.
- The air flow needed in compost reactors was considered in the range of 2500 to 5000 m^3 per hour, according to experiences from biogas producers in the UK.
- In the air purification process, water in the bio trickling filter must cover 60% of total volume of the tank.
- In the bio trickling filter, the recovery of water was 10% of total water requirement per month.
- Density of compost measured in pilot-scale experiments was 340 kg/m^3.
- To estimate energy content in biogas, a 20 MJ per m^3 content was considered for biogas with around 55% of methane. An electrical conversion efficiency of 35% was assumed (32).

- Excess percolate in percolate tanks were considered as 5% of total percolate mass and sent to liquid effluents tank.
- Liquid effluents from the facility were considered according to results from pilot-scale evaluation. Leachate rate of initial mixture was 1L per ton of waste.

Process description for the selected Scenario (SC1)

The process description presented in this section is developed for scenario 1 (SC1), this is the most recommended scenario according to the results presented in Section 1. Please refer to Process Flow Diagrams ADSC-SC1-001 and ADSC-SC1-002 to complement the reading of the following process description.

The dry anaerobic digestion facility receives stackable OFMSW and MGW with high total solids (>20%). MGW is used as a co-substrate to mitigate negative effects of undesirable materials, according to the results of laboratory and pilot scale experiments a 50/50 weight ratio is recommended. In this facility organics are mixed and sent to garage type, gas tight, concrete reactors (fermentation chambers or digesters) using a mechanical loading shovel with no pre-processing required. This plant contemplates percolate recirculation to maintain biomass activity through an external percolate storage system. The fermentation process occurs in the range of 35-40°C and biogas is produced, stored, and sent to use as fuel in a combustion engine to produce electricity. Batch operation mode was considered first due to the modularity of the system, this allows to increase amounts of materials to manage by additional fermenters. According to experiences of biogas producers from the UK, the minimum number of reactors is three, to ensure biogas availability to feed the engine.

The process starts with the reception of OFSMW and MGW at the receiving bay (AD-1), both substrates are transported to the facility by collection trucks (1,2). At the receiving bay, useless waste is manually separated (5) and sent to the others collection bin (AD-T1), to be stored and sent to landfills by collection trucks once a week (72). Screened waste (3) is sent to manual sorting (AD-2) in which operators separate manually recyclables (6) such as glass, plastics, metal, and paper. Recyclable materials are sent to the recyclables bin (AD-T2) and stored to be collected by waste collectors from Sabana Centro (73). Receiving of waste (AD-1) and manual sorting processes (AD-2) are performed in the same area of the plant. OFMSW and MGW are assumed to be delivered on different days of the week. However, the receiving and manual sorting area were designed to have enough capacity to receive both at the same time. Rich organic fraction (4) is sent to the storage bay (AD-T3) in which substrates are mixed and stored until a fermentation chamber is available. The storage bay is equipped with extractors in the ceiling and leachate collection pipes. Once a fermentation chamber is available, mixed organics are sent to anaerobic digestion (7). The supply of biomass to the reactors is performed every 28-35 days. To ensure biogas and methane productivity, the feeding of reactors requires the extraction of partially fermented material within the chamber. A portion of extracted biomass is used as inoculum (44,45,46,47,48,49), sent to the storage bay (AD-T3) and mixed with fresh substrates in an approximate ratio of 45/55 using a front loader. This ratio may be adjusted to accommodate possible variations in the substrate composition. The total mixture (8,9,10,11,12,13) is sent to bioreactors (AD-R1-R2-R3-R4-R5-R6).

The plant is equipped by six anaerobic reactors (AD-R1-R2-R3-R4-R5-R6) arranged in two trains (train 1: AD-R1-R2-R3 and train2: AD-R4-R5-R6) with an inner floor area of 8m x 24m and an internal height of 5m. However, the biomass must not exceed 4 m to store accumulated gases and avoid an increase in internal pressure. Fermentation chambers are built in concrete and are gas tight to prevent oxygen infiltration and biogas leakage. An in-floor heating system maintains the chamber at a constant temperature of 35-40°C. After the reactors are loaded, doors are closed and sealed, and the mixtures are kept inside for approximately 30 days. Biomass is fermented and biogas is produced. When biogas production is ended, air concentration inside the reactors is continuously measured to ensure that the reactors are not opened before all the biogas is drawn and safe levels of CO_2 and H_2S are reached.

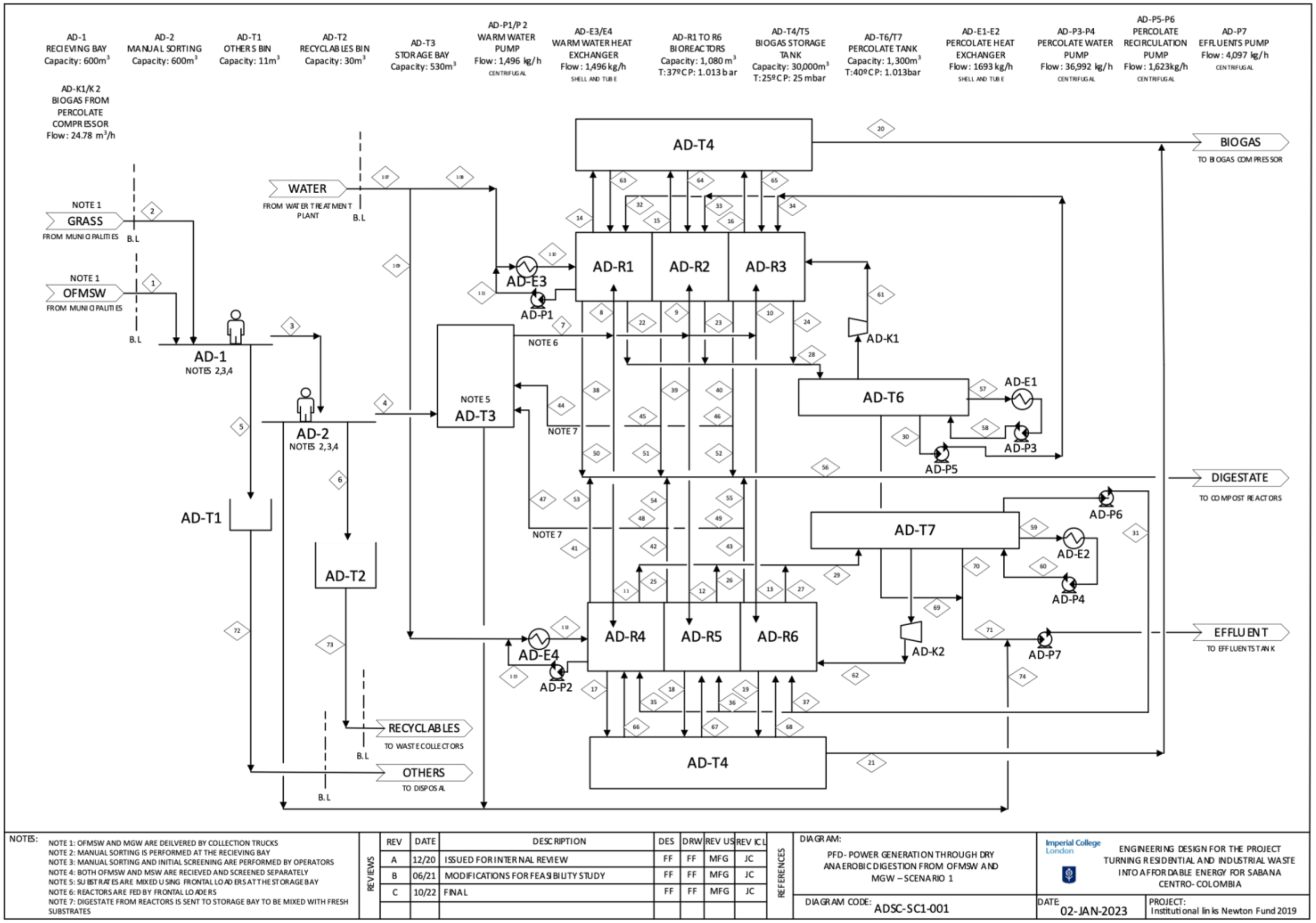
The stability of the fermentation process is improved by the recirculation of percolate. In the reactors, the ceilings are equipped with sprinkles to spray the biomass with heated percolate (train 1: 32,33,34 and train 2: 35,36,37). This percolate inoculates the mixture, keeping its moisture in more than 70%. Percolate recirculation helps in both acidogenesis and methanogenesis. Percolate is collected from the chambers floor through stainless steel gutters with grating (train 1: 22,23,24 and train 2: 25,27,27). Then, the percolate (28,29) is routed to the percolate tanks (AD-T6 and AD-T7). The percolate tanks (AD-T6 and AD-T7) are equipped with inlet pipe end, filling level sensors to switch the pumps, transfer pumps with pipes to the chamber sprinkling system, heating through walls, temperature and pressure sensors, access doors, and a connection to a fermentation chamber. Percolate tanks are heated through heat exchangers (AD-E1 and AD-E2) using warm water (110,112). The capacity of percolate tanks is estimated considering the possibility of adding excess water or a different source of inoculum for startup. Percolate is pumped to each individual reactor through HDPE pipes connected to the sprinkling unit. If the percolate level is too high, excess percolate (69,70) is sent to the effluent tank (E-T1). Warm water (106) is used to maintain the temperature in the reactors through the floor heating system. Water (107, 110) is sent to the heat exchangers AD-E3 and AD-E4, water is heated and channeled to the reactors (108, 111) and then recirculated to heating (109,112).

The biogas produced during fermentation (train 1: 14,15,16 and train 2: 17,18,19) is extracted from the reactors with an explosion and leak proof ventilation system and collected through stainless-steel pipes with gas storage bags located above the reactors (AD-T4 and AD-T5). Gas composition is measured with a gas analysis device. The resulting biogas from each reactor will have different methane contents. However, streams from each reaction train (20,21) will be mixed (22) and resulting biogas will have an average methane concentration (around 54% is aspired). The moist from the biogas is removed in the storage tanks (AD-T4 and AD-T5) by passive condensation extraction, water in the gas is condensed while cooling to ambient temperature and is transferred though a water duct to the reactor chambers (train 1:63,64,65 and train 2: 66,67,68). Biogas is also produced in the percolate tanks; each tank has a connection in the ceiling to a reactor (61,62) and biogas is exhausted. Biogas from anaerobic digestion reactors (77) is sent to the gas engine (P-GE1) through a gas compressor (E-K1). Compressed biogas (95) is combined with air (79) and sent to the gas engine to produce power (78). The electricity produced by the engine is fed into the national grid and used for internal consumption.

During the fermentation process, a solid digestate is produced (train 1: 38, 39, 40 and train 2: 41,42,43). A part of the digestate (train 1: 44, 45,46 and train 2: 47,48,49) is sent to the storage bay (A-T3) and mixed with fresh materials to be used as inoculum. The remaining digestate (train 1: 50,51,52 and train 2: 53,54,55) from individual chambers is (56) mechanically fed to compost reactors (C-R1-R2-R3) by mechanical front loaders (80, 81, 82). In compost reactors a continuous supply of air is needed (87,88,89) to maintain the digestate for at least 15 days at 55°C. Air from compost reactors (90,91,92) is collected (93) and sent to the bio trickling filter E-FIL1. Solid fertilizer from each compost reactor (83,84,85) is sent to stabilization (86). Stabilization is performed in a fertilizer storage bay C-A4 in which solid material is cooled to ambient temperature. Stabilized fertilizer (104) is sent to the fertilizer shredder (C-M1) and sent to packing (106).

The complete facility has a ventilation system that provides enough ventilation for the fermenter charging and discharging process. The exhaust air from the chambers and storage bay (76), and compost air (93) is discharged to the atmosphere via a biotrickling filter E-FIL1. Gases for cleaning (96) are sent to the filter by the bio trickling filter fan (E-E1). The biotrickling filter uses synthetic materials on which degrading bacteria are immobilized as biofilms. The contaminated air flows through the media bed and the active biofilms degrades odorous compounds. A stream of water (103) needs to be continuously recirculated to pass through the media, making the bed biologically active. Scrubbing water (99) is sent to water treatment, and sludge (100) from the filter to solid management. When makeup water is needed (101), water is sent to the biotrickling water storage tank (E-T2) and pumped to the filter. Clean gas is discharged to the atmosphere (97). Liquid effluents from different parts of the process are collected (75) and sent to the effluents tank E-T1 to further treatment (106) in an industrial water treatment plant.

Finally, the waste management facility will have supervisory control and data acquisition (SCADA), and the entire plant will be automated by PLC. A compressor that produces the necessary compressed air to supply all the pneumatic valves. In an event that needs an emergency stop, pneumatic valves are depressurized automatically. Reactor doors are pneumatically closed during the fermentation process. To open the chambers the control system will give an approval only when concentrations of <3% CH_4, <0.5% of CO_2 and >18% of oxygen are measured. Pneumatic doors on reactors can be opened only with a key. Percolate recirculation systems are also monitored by the control system. Percolate tanks will be equipped with level alarms. Additionally, biogas quantity and quality, temperature, pressure in anaerobic digestion, compost reactors, and biogas tanks, percolate quantities, valve and plant conditions are continuously monitored via the PLC. In biogas storage tanks, internal pressure must not exceed 25 mbar to ensure safe conditions. Pressure control in storage tanks is carried out with mechanical pressure relief valves that direct the excess biogas to a flare. Biogas storage tanks can be loaded only to a maximum of 40% of capacity, this is performed by a level control sensor. Figure 4.9 and Figure 4.10 present the Process Flow Diagrams ADSC-SC1-001 and ADSC-SC1-002, which correspond to SC1.



NOTES:

NOTE 1: OFMSW AND MGW ARE DEILVERED BY COLLECTION TRUCKS
NOTE 2: MANUAL SORTING IS PERFORMED AT THE RECIEVING BAY
NOTE 3: MANUAL SORTING AND INITIAL SCREENING ARE PERFORMED BY OPERATORS
NOTE 4: BOTH OFMSW AND MSW ARE RECIEVED AND SCREENED SEPARATELY
NOTE 5: SUBSTRATES ARE MIXED USING FRONTAL LOADERS AT THE STORAGE BAY
NOTE 6: REACTORS ARE FED BY FRONTAL LOADERS
NOTE 7: DIGESTATE FROM REACTORS IS SENT TO STORAGE BAY TO BE MIXED WITH FRESH SUBSTRATES

REVIEWS

REV	DATE	DESCRIPTION	DES	DRW	REV US	REV ICL
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	JC
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	JC
C	10/22	FINAL	FF	FF	MFG	JC

REFERENCES

DIAGRAM:
PFD- POWER GENERATION THROUGH DRY ANAEROBIC DIGESTION FROM OFMSW AND MGW – SCENARIO 1

ENGINEERING DESIGN FOR THE PROJECT TURNING RESIDENTIAL AND INDUSTRIAL WASTE INTO AFFORDABLE ENERGY FOR SABANA CENTRO- COLOMBIA

DIAGRAM CODE: ADSC-SC1-001

DATE: 02-JAN-2023

PROJECT: Institutional links Newton Fund 2019

Figure 4.9. Process Flow Diagram ADSC-SC1-001 for SC1

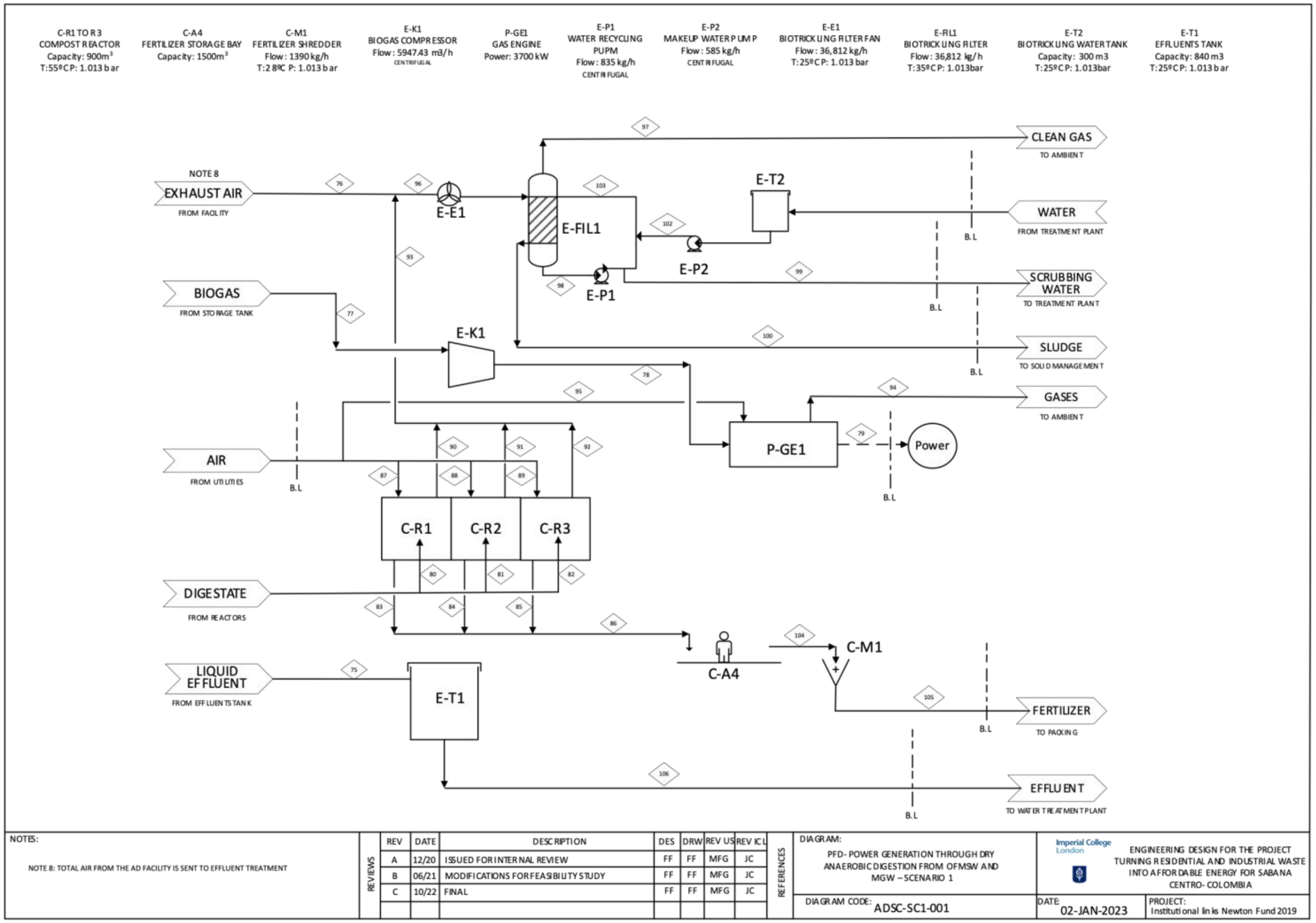


Figure 4.10.Process Flow Diagram ADSC-SC1-002 for SC1

Chapter 5

Concluding remarks

5.1 Overall conclusion

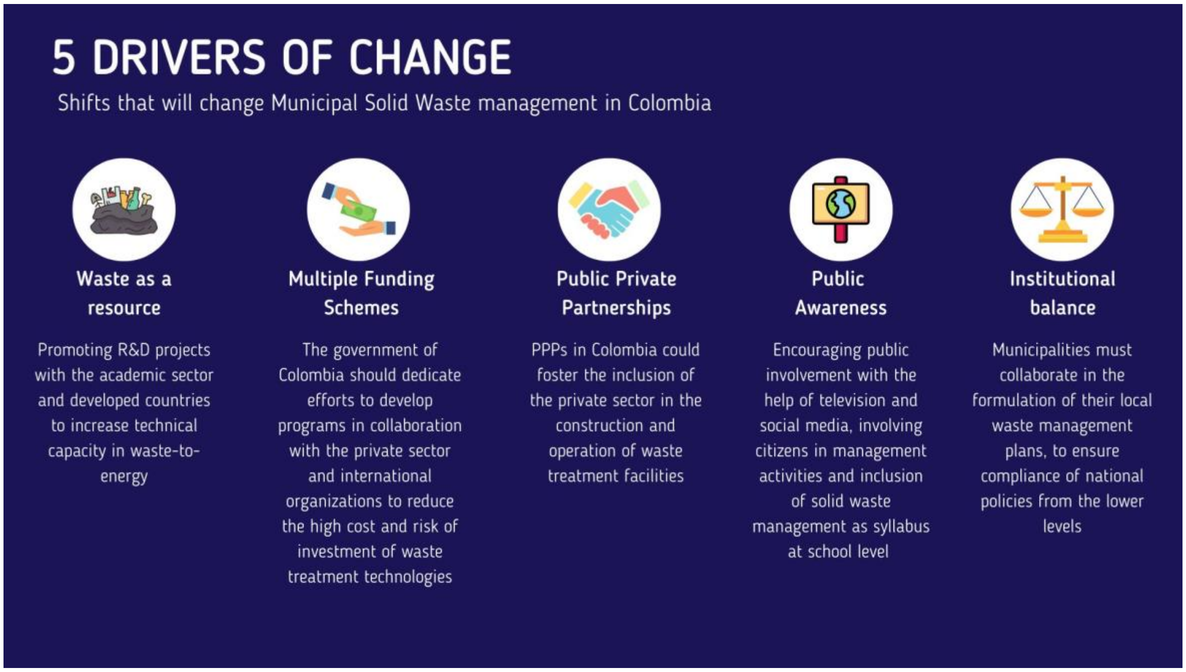
The main idea of this chapter is to come back to the research questions formulated at the beginning of this study: What are the most relevant factors affecting sustainable MSW management in Sabana Centro (Colombia)? How to implement biogas production from OFMSW using dry anaerobic digestion in Sabana Centro? How to design a dry anaerobic digestion plant to treat the OFMSW available in Sabana Centro considering the characteristics of the local context? The research questions proposed during the present study were addressed in three scientific papers and an engineering process design. The main results are summarized and interpreted below.

First question: What are the most relevant factors affecting sustainable MSW management in Sabana Centro (Colombia)?

By using a combined impact analysis and participatory methodology, this study has identified the most relevant factors that affect MSW systems in Sabana Centro. During the analysis, a new classification was proposed, and for the present study, the relevant factors are the ones classified as "First Class". These factors are suitable for actions to improve the performance of the whole system. For the waste management system of Sabana Centro, first class factors are:

- Cost of investment
- Risk of investment
- Local-national level balances
- Waste-to-energy

These factors should serve as a starting point for formulating policies aimed at promoting positive changes in MSW management in Sabana Centro. Based on the identified factors, the study also provides recommendations for Sabana Centro and proposes five drivers of change (Figure 5.1). Moreover, this combined approach can guide researchers in upper-middle income countries to understand the specific dynamics of waste management systems and formulate scientific projects tailored to address local problems. In addition, the approach can support decision-makers in formulating policies focused on factors driving positive changes in the entire MSW system and allocate financial resources towards promoting these changes.



5 DRIVERS OF CHANGE

Shifts that will change Municipal Solid Waste management in Colombia

Waste as a resource

Promoting R&D projects with the academic sector and developed countries to increase technical capacity in waste-to-energy

Multiple Funding Schemes

The government of Colombia should dedicate efforts to develop programs in collaboration with the private sector and international organizations to reduce the high cost and risk of investment of waste treatment technologies

Public Private Partnerships

PPPs in Colombia could foster the inclusion of the private sector in the construction and operation of waste treatment facilities

Public Awareness

Encouraging public involvement with the help of television and social media, involving citizens in management activities and inclusion of solid waste management as syllabus at school level

Institutional balance

Municipalities must collaborate in the formulation of their local waste management plans, to ensure compliance of national policies from the lower levels

Figure 5.1.Five shifts that will change Municipal Solid Waste management in Colombia

Second question: How to improve methane production trough dry anaerobic digestion of source separated OFMSW?

Currently, in Sabana Centro, some municipalities are implementing source-separation policies to obtain the OFMSW and applying composting processes to obtain soil amendments. However, the energy contained in organic waste is not being recovered. Therefore, laboratory scale studies using local waste are essential to define realistic biogas and methane yields and propose efficient process designs for full-scale applications. This study examined the potential for producing biogas from two source separated OFMSW using dry AD under different process conditions. One sample contained cooked and uncooked meat, while the other only fruit and vegetable waste and eggshells The difference between the samples is the presence of cooked and uncooked meat in one of them. Both samples were obtained from two different municipalities in Sabana Centro. Lab-scale experiments revealed that mono-digestion of the sample containing meat residues was not recommended due the formation of toxic inhibitors that limited methane production. Conversely, samples without meat residues showed no inhibition, and methane production was possible. These results highlight the importance of considering the composition of waste samples when evaluating AD for biogas production. The presence of high-protein fractions in the waste can increase nitrogen levels and the risk of accumulation of VFAs, which can lead to process failure. To improve the methane generation process, two strategies were evaluated: anaerobic co-digestion and biological pretreatment using white-rot fungi. In Sabana Centro, MGW is currently untreated or composted. However, due to its low protein and nitrogen content and high carbon, it is a suitable substrate to be mixed with OFMSW, as demonstrated in this study. Both samples tested in the study showed improved process stability and successful methane generation through co-digestion processes, yields are comparable to those reported in the literature. Moreover, fungal pretreatment with white-rot fungi was found to be unsuitable for the tested mixtures. These findings highlight the importance of selecting appropriate strategies to increase methane generation and waste management in different contexts.

The results of laboratory scale experiments have important implications for local authorities in Sabana Centro who are responsible for formulating source separation policies. To ensure consistent feedstock composition, it is recommended that municipalities adopt the same source separation policies for OFMSW. Furthermore, co-digestion of OFMSW and MGW on a 50/50 dry weight basis is recommended to enhance process stability and increase methane yields, particularly when the organic waste contains a high-protein fraction. Additionally, the frequency of organics collection in Cajicá should be increased to minimize aerobic decomposition at the source, which can lead to a decrease in methane production. By implementing these measures, municipalities in Sabana Centro can optimize their organic waste management practices and improve their biogas production potential.

Third question: How to design a dry anaerobic digestion plant to treat the OFMSW available in Sabana Centro considering the characteristics of the local context?

To address this research question, ADPMDesign, a novel methodology to design a biogas power plant from a collective perspective. This methodology enabled to gain a better understanding of the context of implementation. ADPMDesign was applied in Sabana Centro, involving relevant stakeholders from the visualization of the project to the process design stage. Unlike traditional engineering approaches, ADPMDesign allowed engineers to acquire knowledge on technical requirements and address challenges that may arise during the construction and operation of the plant. Researchers in the field of AD can apply ADPMDesign in other Colombian cities and throughout Latin American countries where Municipal Governments are responsible for waste management activities. The results obtained from the application of ADPMDesign in Sabana Centro can be beneficial for stakeholders such as municipal governments, members of the environmental entities, the Public Services Companies, ASOCENTRO, and the Sabana Centro community. Through ADPMDesign, technical feasibility of the co-digestion of OFMSW with MGW to increase methane. The most financially feasible option for Sabana Centro is to build a large-scale municipal plant rather than multiple small-scale plants. This facility would be capable of treating 45,549 tons of OFMSW annually and generating 3.7 MW of electricity. The payback time for the project is estimated to be approximately 5.8 years. To further reduce the payback time to 4.2 years, it is highly recommended for Sabana Centro to market soil amendments produced from the biogas production process.

This study combined participatory approaches with an extensive technical assessment to propose a biogas power plant that is specifically designed for the stakeholders. The barriers identified in the second chapter were taken into consideration in the design proposal. Firstly, the high cost and risk of investment associated to WtE projects can be addressed considering the following recommendations: i) study the possibility of selling electricity to the national grid as large-scale generator, ii) establish collaboration agreements for co-production, management, operation, and maintenance processes, iii) create Joint Ventures to share resources, profits, losses, and expenses, and lastly, iv) establish Public-Private Partnerships for waste management activities. The technical uncertainties related to the implementation of WtE technologies were reduced through extensive laboratory and pilot-scale experiments that demonstrated technical feasibility of biogas production from locally available OFMSW. Additionally, to reduce the imbalance among municipal governments of Sabana Centro, it is important to establish waste management plans with consistent guidelines for source-separation. This will ensure a more coordinated and effective waste management system across the region and reduce technical complexity given by dealing with heterogeneous waste. Municipalities are encouraged to join efforts to support the construction of one large-scale facility to produce electricity from biogas in Sabana Centro and build a plant that could provide electricity for around 12,000 homes.

5.2 Limitations

- During the application of participatory methodologies in Sabana Centro, some limitations were identified. One of the main limitations is coordinating the schedules of all stakeholders to attend workshops, interviews, and focus groups. To prevent delays, it is strongly recommended to schedule stakeholders carefully with sufficient time in advance. Another limitation is related to confidentiality, as information provided by stakeholders can only be used for research purposes by the research team. Therefore, researchers must handle this information carefully.
- During laboratory and pilot-scale experiments, properties of the substrates such as lignin, hemicellulose, and cellulose contents were not determined due to the unavailability of the appropriate equipment and laboratories. Additionally, the pilot plant of the Botanical Garden of Bogotá presented operational failures with air tightness, heating systems, and energy conversion. This was an important limitation; energy balances were made based on assumptions obtained from the literature review.
- During this project, the pandemic COVID-19 was a strong limitation. First, the quarantines made the experimentation phase challenging since everything was closed and the public

services companies were not allowed to provide organic waste. Secondly, purchasing of supplies and equipment suffered a strong delay. Lastly, participatory approaches were also affected by the pandemic and part of the interviews had to be performed virtually.

5.3 Perspectives for future research

Although this thesis has explored dry anaerobic digestion at laboratory and pilot-scales, there are still some improvements that could be implemented. As for example:

- A better understanding of the biological effects of fungal pre-treatments in the organic fraction of municipal solid waste is needed to identify opportunities for improvements or gain knowledge about its effect on inhibition conditions. Additionally, different pre-treatments of the organic fraction of municipal solid waste could be explored. Even though fungal pre-treatment with the white rot fungi was not recommended for this substrate, different biological or other types of pre-treatments can be explored to study their effect on biogas production and methane yields.
- During the experiments we identified the need from stakeholders to use waste-water treatment plant (WWTP) sludges as co-substrate or inoculum during dry anaerobic digestion. However, WWTP in Sabana Centro are small and the management of the sludges affect its qualities to be used for anaerobic digestion. We recommend performing studies to explore alternatives to obtain energy from sludges once the modernization of the plants is finished.
- Further studies can be made to evaluate the reduction on GHG emissions caused by the implementation of both production scenarios proposed during the present study using Life Cycle Assessment methodology. This will complement the recommendation from an environmental perspective.
- This study only contemplated the evaluation of alternatives for OFMSW. However, future research can be performed to handle different MSW fractions such as residual waste.
- Regarding participatory approaches, we recommend the application of ADPMDesign in other Colombian cities to design biogas power plants from OFMSW. Finally, the combined approach applied in the second chapter can be applied in other cities in

Colombia to establish possible differences in waste management systems across the country.

5.3 Research products

5.3.1. Projects

This thesis was funded by two projects:

Project I: Evaluation of a municipal waste-to-energy biogas plant using solid-state anaerobic digestion for Sabana Centro, Colombia.

This project is funded by Ministerio de Ciencia, Tecnología e Innovación (Minciencias), Gobernación de Cundinamarca and the program Colombia BIO 829 [Project number 66181] and was developed by La Universidad de La Sabana, the Botanical Garden of Bogotá (JBB[21]), and the Asociación de Municipios de Sabana Centro (ASOCENTRO[22]), with the support of the Public Services Companies of Cajicá and Chía.

Project II: Turning residential and industrial waste into affordable energy through dry fermentation - Sabana Centro, Colombia - Funded by Newton Fund Institutional Links

This project is funded by The Newton Fund – Institutional Links – June 2019 call and was developed by La Universidad de La Sabana from Colombia, the Imperial College London from the United Kingdom, and the Asociación de Municipios de Sabana Centro (ASOCENTRO).

5.3.2. Scientific Papers

- Franceschi F, Vega LT, Sanches-Pereira A, Cherni JA, Gómez MF. A combined approach to improve municipal solid waste management in upper-middle-income countries: the case of Sabana Centro, Colombia. Clean Technol Environ Policy. 2022. https://doi.org/10.1007/s10098-022-02333-x
- Franceschi F, Castillo JS, Cherni JA, Acosta-Gonzalez A, Gómez MF. ADPMDesign: The use of a Participatory Methodology to Design a dry anaerobic digestion power plant

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[21] In Spanish, The Botanical Garden of Bogotá

[22] In Spanish, Asociación de Municipios de Sabana Centro

for municipal solid waste treatment. Energy for Sustainable Development. 2023. https://doi.org/10.1016/j.esd.2023.03.017

- Franceschi F, Acosta-Gonzalez A, Vega LT, Gómez MF. Improving dry anaerobic methane production from OFMSW by co-digestion with grass waste and pretreatment with white rot fungi. Accepted for Publication. Energy for Sustainable Development. 2023.

5.3.3. Participation in International Conferences

Barriers for a Municipal Solid Waste management in Colombia. International Society for Industrial Ecology ISIE Americas. 2020.

Lessons for the design of garage type dry anaerobic digestion pilot plants: the case of the Botanical Garden of Bogota. BERSTIC[23]. 2022

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[23] In Spanish, Biorrefinerías y Energías Renovables Soportadas en TIC

Appendix I

Mass and energy balances for the dry anaerobic digestion production scenarios

In this Appendix, mass and energy balances developed for different production scenarios are presented. First, Table 1 shows balances of production scenario 1 for Sabana Centro, this scenario contemplates the construction of one municipal plant that will receive OFMSW generation capacity of the eleven municipalities of Sabana Centro by 2030. Secondly, Table 2 present balances of scenario 2 for Sabana Centro, which considers the construction of three municipal plants with the same capacity, located near the three municipalities with the highest OFMSW generation in the province: Chia, Cajicá, and Zipaquirá. The capacity of each plant was estimated based on the clustering of municipalities and projected for 2030. Both scenarios for Sabana Centro were developed as part of the second project related to the objectives of this thesis "Turning residential and industrial waste into affordable energy through dry fermentation - Sabana Centro, Colombia - Funded by Newton Fund Institutional Links". Finally, a different scenario named "Cajicá" is also presented. The scenario Cajicá shows the balances for a small plant designed to process OFMSW only from Cajicá by 2025. Process design developed for Cajicá was part of the first project related to the objectives of this thesis "Evaluation of a municipal waste-to-energy biogas plant using solid-state anaerobic digestion for Sabana Centro, Colombia". In this project, a preliminary technical proposal was developed for Cajicá.

1. Scenario 1 (SC1): one municipal dry AD facility for Sabana Centro

Table 1. Balances of the municipal dry anaerobic digestion facility for Sabana Centro (Scenario 1)

Stream	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	SS-OFMSW	Grass	Screened waste	Rich organics	Others to storage	Recyclables to storage	Feedstock to AD	Feed R1	Feed R2	Feed R3	Feed R4	Feed R5	Feed R6	Biogas R1	Biogas R2	Biogas R3
T (ºC)	25	25	25	28	25	25	25	25	25	25	25	25	25	35	35	35
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	3795,68	3567,9392	7289,983	6925,48386	73,64	364,50	6925,48	2167,37	2167,37	2167,37	2167,37	2167,37	2167,37	1255,54	1255,54	1255,54
v (m3/month)	-	-	-	-	-	-	-	-	-	-	-	-	-	534592,64	534592,64	534592,64
MW (kg/kmol)	-	-	-	-	-	-	-	-	-	-	-	-	-	29,56	29,56	29,56
								Composition								
Methane	-	-	-	-	-	-	-	-	-	-	-	-	-	53,00	53,00	53,00
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	-	-	-	46,94	46,94	46,94
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-	120	120	120
Water	-	-	-	-	-	-	-	-	-	-	-	-	-	0,05	0,05	0,05
OFMSW	100	-	100	100	-	-	51,52	27	27	27	27	27	27	-	-	-
Digestate	-	-	-	-	-	-	-	46	46	46	46	46	46	-	-	-
Grass	-	100	-	-	-	-	48,43	27	27	27	27	27	27	-	-	-
Inorganics	-	-	-	-	-	100	-	-	-	-	-	-	-	-	-	-
Metallics	-	-	-	-	100	-	-	-	-	-	-	-	-	-	-	-

Stream	17 Biogas R4	18 Biogas R5	19 Biogas R6	20 Biogas from train 1	21 Biogas from train 2	22 Percolate R1	23 Percolate R2	24 Percolate R3	25 Percolate R4	26 Percolate R5	27 Percolate R6	28 Percolate to tank 1	29 Percolate to tank 2	30 Percolate to train 1	31 Percolate to train 2	32 Percolate to R1
T (ºC)	35	35	35	25	25	35	35	35	35	35	35	28	28	45	45	42
P (bar)	1,013	1,013	1,013	0,025	0,025	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	1255,54	1255,54	1255,54	3766,61	3766,61	429,14	429,14	429,14	429,14	429,14	429,14	1287,42	1287,42	1287,42	1287,42	429,14
v (m3/month)	534592,64	534592,64	534592,64	1129246,66	1129246,66	433,47	433,47	433,47	433,47	433,47	433,47	1300,42	1300,42	1300,42	1300,42	433,47
MW (kg/kmol)	29,56	29,56	29,56	29,56	29,56	-	-	-	-	-	-	-		-	-	-
Composition																
Methane	53,00	53,00	53,00	53,00	53,00	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	46,94	46,94	46,94	46,94	46,94	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	120	120	120	120	120	-	-	-	-	-	-	-	-	-	-	-
Water	0,05	0,05	0,05	0,05	0,05	-	-	-	-	-	-	-	-	-	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	-	100	100	100	100	100	100	100	100	100	100	100

Stream	33 Percolate to R2	34 Percolate to R3	35 Percolate to R4	36 Percolate to R5	37 Percolate to R6	38 Digestate R1	39 Digestate R2	40 Digestate R3	41 Digestate R4	42 Digestate R5	43 Digestate R6	44 Digestate to R1	45 Digestate to R2	46 Digestate to R3	47 Digestate to R4	48 Digestate to R5
T (ºC)	42	42	42	42	42	35	35	35	35	35	35	28	28	28	28	28
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	429,14	429,14	429,14	429,14	429,14	1924,95	1924,95	1924,95	1924,95	1924,95	1924,95	1013,12	1013,12	1013,12	1013,12	1013,12
v (m3/month)	433,47	433,47	433,47	433,47	433,47	-	-	-	-	-	-	-	-	-	-	-
MW (kg/kmol)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Composition																
Methane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Water	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	100	100	100	100	100	100	100	100	100	100	100
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	100	100	100	100	100	-	-		-	-		-	-	-	-	-

Stream	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
	Digestate to R6	Digestate to compost R1	Digestate to compost R2	Digestate to compost R3	Digestate to compost R4	Digestate to compost R5	Digestate to compost R6	Digestate to compost	Water to percolate E1	Water from percolate E1	Water to percolate E2	Water from percolate E2	Biogas from percolate train 1	Biogas from percolate train 2	Water from R1	Water from R2
T (ºC)	28	28	28	28	28	28	28	28	95	75	95	75	35	35	25	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	0,025	0,025
m (tons/month)	1013,12	911,83	911,83	911,83	911,83	911,83	911,83	5470,97	29339,98	29339,98	29339,98	29339,98	26,52	26,52	169	169
v (m3/month)	-	-	-	-	-	-	-	-	-	-	-	-	11292,47	11292,47	154,09	154,09
MW (kg/kmol)	-	-	-	-	-	-	-	-	18	18	18	18	29,56	29,56	18	18
Composition																
Methane	-	-	-	-	-	-	-	-	-	-	-	-	53,00	53,00	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	-	-	46,94	46,94	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	120	120	-	-
Water	-	-	-	-	-	-	-	-	100	100	100	100	0,05	0,05	100	100
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	100	100	100	100	100	100	100	100	-	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Stream	Water from R3	Water from R4	Water from R5	Water from R6	Effluents from percolate train 1	Effluents from percolate train 1	Effluents from percolate	Plastics	Others	Effluents from facility	Effluents to tank	Exhaust air	Biogas to power	Biogas to engine	Power	Digestate to compost R1
T (ºC)	25	25	25	25	45	45	45	25	28	28	28	25	25	15	-	28
P (bar)	0,005	0,005	0,025	0,025	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	0,025	1,013	-	1,013
m (tons/month)	169	169	169	169	64,37	64,37	128,74	364,50	73,64	3121,01	3249,75	17,64	7533,22	7533,22	-	1823,66
v (m3/month)	154,09	154,09	154,09	154,09	65,02	65,02	130,04	-	-	3152,53	3282,57	75	2258493,32	1355095,99	-	-
MW (kg/kmol)	18	18	18	18	-	-	-	-	-	-	-	-	29,56	29,56	-	-
Energy (kW)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**3659,60**	-
Composition																
Methane	-	-	-	-	-	-	-	-	-	-	-	-	53,00	53,00	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	-	-	46,94	46,94	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	120	120	-	-
Water	100	100	100	100	-	-	-	-	-	-	-	-	0,05	0,05	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	100	100	100	-	-	100	100	-	-	-	-	-
Plastics	-	-	-	-	-	-	-	100	-	-	-	-	-	-	-	-
Others	-	-	-	-				-	100	-	-	-	-	-	-	-
Air	-	-	-	-	-	-	-	-	-	-	-	80	-	-	-	-
Traces	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
Fertilizer	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
Stream	Digestate to compost R2	Digestate to compost R3	Fertilizer to stabilization R1	Fertilizer to stabilization R2	Fertilizer to stabilization R3	Fertilizer to stabilization	Air to compost R1	Air to compost R2	Air to compost R3	Gases from R1	Gases from R2	Gases from R3	Gases from compost	Combustion gases	Air to engine	Air to filter
T (ºC)	28	28	55	55	55	25	28	28	28	25	25	25	25	25	500	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,2	1,013
m (tons/month)	1823,66	1823,66	367	367	367	1102	1677,10	1677,10	1677,10	559,03	559,03	559,03	1677,10	30778,05	23244,83	1694,74
v (m3/month)	-	-	-	-	-	-	1416,67	1416,67	1416,67	1559,1	1559,1	1559,1	4677,3	-	39019440	-
MW (kg/kmol)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Composition																
Methane	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	5
Carbon dioxide	-	-	-	-	-	-	-	-	-	28	28	28	28	49		49
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-	28	-	28
Water	-	-	-	-	-	-	-	-	-	5	5	5	5	10	-	8
Digestate	100	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	-	-	100	100	100	63	63	63	63	8	100	8
Traces	-	-	-	-	-	-	-	-	-	4	4	4	4	-	-	2
Fertilizer	-	-	100	100	100	100	-	100	-	-	-	-	-	-	-	-

Stream	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113
	Clean air	Water from filter	Scrubbing water	Sludge from filter	Water to tank	Makeup water	Water recycling to filter	Fertilizer to shredding	Fertilizer to packing	Effluents to treatment plant	Water to reactors	Water to train 1	Water to train 2	Warm water to train 1	Cold water from train 1	Warm water to train 2	Cold water from train 2
T (ºC)	35	35	35	35	25	25	35	25	25	28	25	25	25	95	75	95	75
P (bar)	1,013	1,013	1,2	1,013	1,013	1,013	1,2	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	1032,24	662,50	101,68	1016,84	463,75	463,75	662,5	1102	1102	3249,75	2373,74	1186,87	1186,87	1186,87	1186,87	1186,87	1186,87
v (m3/month)	-	722,125	-	-	722,125	722,125	722,125	-	-	3282,57	21548,78	10774,39	1077,4	1112,36	1105,25	1112,36	1105,25
MW (kg/kmol)	-	18	18	-	18	18	18	-	-	-	18	18	18	18	18	18	18
Composition																	
Methane	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Water	-	100	100	5	100	100	100	-	-	-	100	100	100	100	100	100	100
Digestate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	95	-	-	-	-	-	100	-	-	-	-	-	-	-
Air	98	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Traces	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fertilizer	-	-	-	-	-	-	-	100	100	-	-	-	-	-	-	-	-

2. Scenario 2 (SC2): three municipal dry AD facilities for Sabana Centro

Table 2. Balances of the dry anaerobic digestion facility for Sabana Centro (Scenario 2)

Stream	1 SS-OFMSW	2 Grass	3 Screened waste	4 Rich organics	5 Others to storage	6 Recyclables to storage	7 Feedstock to AD	8 Feed R1	9 Feed R2	10 Feed R3	11 Biogas R1	12 Biogas R2	13 Biogas R3
T (ºC)	25	25	25	28	25	25	25	25	25	25	35	35	35
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	1339,11	1258,76	2571,89	2443,30	25,98	128,59	2443,30	1529,29	1529,29	1529,29	980,52	980,52	980,52
v (m3/month)	-	-	-	-	-	-	-	-	-	-	417492,32	417492,32	417492,32
MW (kg/kmol)	-	-	-	-	-	-	-	-	-	-	29,56	29,56	29,56
Composition													
Methane	-	-	-	-	-	-	-	-	-	-	53,00	53,00	53,00
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	46,94	46,94	46,94
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	120	120	120
Water	-	-	-	-	-	-	-	-	-	-	0,05	0,05	0,05
OFMSW	100	-	100	100	-	-	51,52	27	27	27	-	-	-
Digestate	-	-	-	-	-	-	-	46	46	46	-	-	-
Grass	-	100	-	-	-	-	48,43	27	27	27	-	-	-
Inorganics	-	-	-	-	-	100	-	-	-	-	-	-	-
Metalics	-	-	-	-	100	-	-	-	-	-	-	-	-

Stream	14 Biogas to storage	15 Percolate R1	16 Percolate R2	17 Percolate R3	18 Percolate to heating	19 Percolate to reactors	20 Percolate to R1	21 Percolate to R2	22 Percolate to R3	23 Digestate R1	24 Digestate R2	25 Digestate R3	26 Digestate to R1
T (ºC)	25	35	35	35	30	45	42	42	42	35	35	35	28
P (bar)	0,025	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	2941,55	151,40	151,40	151,40	454,20	454,20	151,40	151,40	151,40	1263,62	1263,62	1263,62	714,85
v (m3/month)	881889,83	152,93	152,93	152,93	458,79	458,79	152,93	152,93	152,93	-	-	-	-
MW (kg/kmol)	29,555621	-	-	-	-	-	-	-	-	-	-	-	-
Composition													
Methane	53,00	-	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	46,94	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	120	-	-	-	-	-	-	-	-	-	-	-	-
Water	0,05	-	-	-	-	-	-	-	-	-	-	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	-	-	-	-	100	100	100	100

Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	100	100	100	100	100	100	100	100	-	-		-

Stream	27 Digestate to R2	28 Digestate to R3	29 Digestate to compost R1	30 Digestate to compost R2	31 Digestate to compost R3	32 Digestate to compost	33 Water to percolate heating	34 Water from percolate heating	35 Biogas from percolate tank	36 Effluents from percolate	37 Water from R1	38 Water from R2	39 Water from R3
T (ºC)	28	28	28	28	28	28	75	95	35	45	25	25	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	0,025	0,025	0,025
m (tons/month)	714,85	714,85	548,77	548,77	548,77	1646,31	10351,10	10351,10	20,71	22,71	132	132	132
v (m3/month)	-	-	-	-	-	-	-	-	8818,90	22,94	120,34	120,34	120,34
MW (kg/kmol)	-	-	-	-	-	-	18	18	29,56	-	18	18	18
Composition													
Methane	-	-	-	-	-	-	-	-	53,00	-	-	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	46,94	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	120	-	-	-	-
Water	-	-	-	-	-	-	100	100	0,05	-	100	100	100
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	100	100	100	100	100	100,00	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	-	-	-	-	-	100	-	-	-

Stream	40	41	42	43	44	45	46	47	48	49	50	51	52
	Plastics	Others	Effluents from facility	Effluents to tank	Exhaust air	Biogas to engine	Power	Exhaust gases	Air from compost area	Air to compost	Fertilizer to stabilization	Fertilizer to shredder	Fertilizer to packing
T (ºC)	25	28	28	28	25	15	-	25	55	28	55	25	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	-	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	128,59	25,98	550,54	573,25	2,94	2941,55	-	3769,44	431,415	431	1646	1646	1646
v (m3/month)	-	-	556,10	579,04	75	529133,90	-	-	364108,05	2751,13	-	-	-
MW (kg/kmol)	-	-	-	-		29,56	-	-	13,42	-	-	-	-
Energy (kW)	-	-	-	-		-	1428,99	-	-	-	-	-	-
Composition													
Methane	-	-	-	-	-	53,00	-	5	1	-	-	-	-
Carbon dioxide	-	-	-	-	-	46,94	-	49	28	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	120	-	28	12	-	-	-	-
Water	-	-	-	-	-	0,05	-	10	5	-	-	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	-	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	100	100	-	-	-	-	-	-	-	-	-
Plastics	100	-	-	-	-	-	-	-	-	-	-	-	-
Others	-	100	-	-	-	-	-	-	-	-	-	-	-
Air	-	-	-	-	80	-	-	8	63	100	-	-	-
Traces	-	-	-	-	2	-	-	-	4	-	-	-	-
Fertilizer	-	-	-	-	-	-	-	-	-	-	100	100	100

Stream	53	54	55	56	57	58	59	60	61	62	63	64	65
	Effluents to treatment plant	Air to cleaning	Clean air	Water from filter	Scrubbing water	Sludge from filter	Water to tank T2	Makeup water	Water recycling to filter	Air to engine	Water to reactors	Warm water to reactors	Cold water from reactors
T (ºC)	28	25	35	35	35	35	25	25	35	25	25	95	75
P (bar)	1,013	1,013	1,013	1,013	1,2	1,013	1,2	1,013	1,2	1,2	1,013	1,013	1,013
m (tons/month)	573,25	434,36	434,36	220,83	26,06	260,61	154,58	154,58	220,83	827,89	837,45	837,45	837,45
v (m3/month)	579,04	333075,18	-	240,71	-	-	240,71	240,71	240,71	535917,9	7602,3625	784,87	779,86
MW (kg/kmol)	-	-	-	18	18	-	18	18	18	-	18	18	18
Composition													
Methane	-	5	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	-	49	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	-	28	-	-	-	-	-	-	-	-	-	-	-
Water	-	8	-	100	100	5	100	100	100	-	100	100	100
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	100	-	-	-	-	-	-	-	-	-	-	-	-
Sludge	-	-	-	-	-	95	-	-	-	-	-	-	-
Air	-	8	98	-	-	-	-	-	-	100	-	-	-
Traces	-	2	2	-	-	-	-	-	-	-	-	-	-
Fertilizer	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3. Balances of the municipal dry anaerobic digestion facility for Cajicá, Sabana Centro

Stream	1	2	3	4	5	6	7	8	9	10	11	12	13
	SS-OFMSW	Grass	Screened waste	Rich organics	Others to storage	Recyclables to storage	Feedstock to AD	Feed R1	Feed R2	Feed R3	Biogas R1	Biogas R2	Biogas R3
T (ºC)	25	25	25	28	25	25	25	25	25	25	35	35	35
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	650	611,325	1248,71	1186,28	12,61	62,44	1186,28	742,60	742,60	742,60	476,12	476,12	476,12
v (m3/month)	-	-	-	-	-	-	-	-	-	-	202727,73	202727,73	202727,73
MW (kg/kmol)	-	-	-	-	-	-	-	-	-	-	29,56	29,56	29,56
Composition													
Methane	-	-	-	-	-	-	-	-	-	-	53,00	53,00	53,00
Carbon dioxide	-	-	-	-	-	-	-	-	-	-	46,94	46,94	46,94
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	-	-	120	120	120

Water	-	-	-	-	-	-	-	-	-	-	0,05	0,05	0,05
OFMSW	100	-	100	100	-	-	51,51	27	27	27	-	-	-
Digestate	-	-	-	-	-	-	-	46	46	46	-	-	-
Grass	-	100	-	-	-	-	48,44	27	27	27	-	-	-
Inorganics	-	-	-	-	-	100	-	-	-	-	-	-	-
Metallics	-	-	-	-	100	-	-	-	-	-	-	-	-

Stream	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	Biogas to storage	Percolate R1	Percolate R2	Percolate R3	Percolate to heating	Percolate to reactors	Percolate to R1	Percolate to R2	Percolate to R3	Digestate R1	Digestate R2	Digestate R3	Digestate to R1
T (ºC)	25	35	35	35	30	45	42	42	42	35	35	35	28
P (bar)	0,025	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	1428,37	73,52	73,52	73,52	220,55	220,55	73,52	73,52	73,52	613,65	613,65	613,65	347,17
v (m3/month)	428231,88	74,26	74,26	74,26	222,78	222,78	74,26	74,26	74,26	-	-	-	-
MW (kg/kmol)	29,5556213	-	-	-	-	-	-	-	-	-	-	-	-
							Composition						
Methane	53,00	-	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	46,94	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	120	-	-	-	-	-	-	-	-	-	-	-	-
Water	0,05	-	-	-	-	-	-	-	-	-	-	-	-
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	-	-	-	-	-	-	-	-	-	100	100	100	100
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	100	100	100	100	100	100	100	100	-	-		-

	27	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Stream	Digestate to R2	Digestate to R3	Digestate to compost R1	Digestate to compost R2	Digestate to compost R3	Digestate to compost	Water to percolate heating	Water from percolate heating	Biogas from percolate tank	Effluents from percolate	Water from R1	Water from R2	Water from R3
T (ºC)	28	28	28	28	28	28	95	75	35	45	25	25	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	1,013	0,025	0,025	0,025
m (tons/month)	347,17	347,17	266,47	266,47	266,47	799,42	5026,33	5026,33	10,06	11,03	64	64	64
v (m3/month)	-	-	-	-	-	-	-	-	4282,32	11,14	58,43	58,43	58,43
MW (kg/kmol)	-	-	-	-	-	-	18	18	29,56	-	18	18	18
Composition													
Methane	-	-	-	-	-	-	-	-	53,00	-	-	-	-
Carbon dioxide	-	-	-	-	-	-	-	-	46,94	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	-	-	-	120	-	-	-	-
Water	-	-	-	-	-	-	100	100	0,05	-	100	100	100
OFMSW	-	-	-	-	-	-	-	-	-	-	-	-	-
Digestate	100	100	100	100	100	100,00	-	-	-	-	-	-	-
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	-	-	-	-	-	-	-	-	-	100	-	-	-

Stream	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**
	Plastics	Others	Effluents from facility	Effluents to tank	Exhaust air	Biogas to engine	Power	Exhaust gases	Air from compost area	Air to compost	Fertilizer to stabilization	Fertilizer to shredder	Fertilizer to packing
T (ºC)	25	28	28	28	25	15	-	25	55	28	55	25	25
P (bar)	1,013	1,013	1,013	1,013	1,013	1,013	-	1,013	1,013	1,013	1,013	1,013	1,013
m (tons/month)	62,44	12,61	267,34	278,36	2,94	1428,37	-	1925,11	287,61	288	799	799	799
v (m3/month)	-	-	270,04	281,17	75	256939,13	-	1476222,68	242738,70	2751,13	-	-	-
MW (kg/kmol)	-	-	-	-		29,56	-	24,26	13,42	-	-	-	-
Energy (kW)	-	-	-	-			693,89	-	-	-	-	-	-
Composition													
Methane	-	-	-	-	-	53,00	-	5	1	-	-	-	-
Carbon dioxide	-	-	-	-	-	46,94	-	49	28	-	-	-	-
Hydrogen sulfide (ppm)	-	-	-	-	-	120	-	28	12	-	-	-	-
Water	-	-	-	-	-	0,05	-	10	5	-	-	-	-
OFMSW	-	-	-	-	-		-	-	-	-	-	-	-
Digestate	-	-	-	-	-		-	-	-	-	-	-	-
Grass	-	-	-	-	-		-	-	-	-	-	-	-
Percolate	-	-	100	100	-		-	-	-	-	-	-	-
Plastics	100	-	-	-	-		-	-	-	-	-	-	-
Others	-	100	-	-	-		-	-	-	-	-	-	-
Air	-	-	-	-	80		-	8	63	100	-	-	-
Traces	-	-	-	-	2		-	-	4	-	-	-	-
Fertilizer	-	-	-	-	-		-	-	-	-	100	100	100

Stream	53 Effluents to treatment plant	54 Air to cleaning	55 Clean air	56 Water from filter	57 Scrubbing water	58 Sludge from filter	59 Water to tank T2	60 Makeup water	61 Water recycling to filter	62 Air to engine	63 Water to reactors	64 Warm water to reactors	65 Cold water from reactors
T (ºC)	28	25	35	35	35	35	25	25	35	25	25	95	75
P (bar)	1,013	1,013	1,013	1,013	1,2	1,013	1,2	1,013	1,2	1,2	1,013	1,013	1,013
m (tons/month)	278,36	290,55	290,55	132,50	17,43	174,33	92,75	92,75	132,5	496,734	406,65	406,65	406,65
v (m3/month)	281,17	222801,61	-	144,425	-	-	144,425	144,425	144,425	321551	3691,58809	381,12	378,69
MW (kg/kmol)	-	-	-	18	18	-	18	18	18	-	18	18	18
Composition													
Methane	-	5	-	-	-	-	-	-	-	-	-	-	-
Carbon dioxide	-	49	-	-	-	-	-	-	-	-	-	-	-
Hydrogen sulfide (ppm)	-	28	-	-	-	-	-	-	-	-	-	-	-
Water	-	8	-	100	100	5	100	100	100	-	100	100	100
Grass	-	-	-	-	-	-	-	-	-	-	-	-	-
Percolate	100	-	-	-	-	-	-	-	-	-	-	-	-
Sludge	-	-	-	-	-	95	-	-	-	-	-	-	-
Air	-	8	98	-	-	-	-	-	-	100	-	-	-
Traces	-	2	2	-	-	-	-	-	-	-	-	-	-
Fertilizer	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix II

Process description for the dry anaerobic digestion production scenarios

Process descriptions for the different production scenarios are presented in this Appendix. First, process description of production scenario 1 for Sabana Centro is presented, this scenario contemplates the construction of one municipal plant that will receive OFMSW generation capacity of the eleven municipalities of Sabana Centro by 2030. Secondly, scenario 2 for Sabana Centro is described, this scenario considered the construction of three municipal plants with the same capacity, located near the three municipalities with the highest OFMSW generation in the province: Chia, Cajicá, and Zipaquirá. Finally, the scenario Cajicá shows the balances for a small plant designed to process OFMSW only from Cajicá by 2025.

1. **Scenario 1 (SC1): one municipal dry AD facility for Sabana Centro**

The dry anaerobic digestion facility receives stackable OFMSW and MGW with high total solids (>20%). MGW is used as a co-substrate to mitigate negative effects of undesirable materials, according to the results of laboratory and pilot scale experiments a 50/50 weight ratio is recommended. In this facility organics are mixed and sent to garage type, gas tight, concrete reactors (fermentation chambers or digesters) using a mechanical loading shovel with no pre-processing required. This plant contemplates percolate recirculation to maintain biomass activity through an external percolate storage system. The fermentation process occurs in the range of 35-40°C and biogas is produced, stored, and sent to use as fuel in a combustion engine to produce electricity. Batch operation mode was considered first due to the modularity of the system, this allows to increase amounts of materials to manage by additional fermenters. According to experiences of biogas producers from the UK, the minimum number of reactors is three, to ensure biogas availability to feed the engine.

The process starts with the reception of OFSMW and MGW at the receiving bay (AD-1), both substrates are transported to the facility by collection trucks (1,2). At the receiving bay, useless waste is manually separated (5) and sent to the others collection bin (AD-T1), to be stored and sent to landfills by collection trucks once a week (72). Screened waste (3) is sent to manual sorting (AD-2) in which operators separate manually recyclables (6) such as glass, plastics, metal, and paper. Recyclable materials are sent to the recyclables bin (AD-T2) and stored to be collected by waste collectors from Sabana Centro (73). Receiving of waste (AD-1) and manual sorting processes (AD-2) are performed in the same area of the plant. OFMSW and MGW are assumed to be delivered on different days of the week. However, the receiving and manual sorting area were designed to have enough capacity to receive both at the same time. Rich organic fraction (4) is sent to the storage bay (AD-T3) in which substrates are mixed and stored until a fermentation chamber is available. The storage bay is equipped with extractors in the ceiling and leachate collection pipes. Once a fermentation chamber is available, mixed organics are sent to anaerobic digestion (7). The supply of biomass to the reactors is performed every 28-35 days. To ensure biogas and methane productivity, the feeding of reactors requires the extraction of partially fermented material within the chamber. A portion of extracted biomass is used as inoculum (44,45,46,47,48,49), sent to the storage bay (AD-T3) and mixed with fresh substrates in an approximate ratio of 45/55 using a front loader. This ratio may be adjusted to accommodate possible variations in the substrate composition. The total mixture (8,9,10,11,12,13) is sent to bioreactors (AD-R1-R2-R3-R4-R5-R6).

The plant is equipped by six anaerobic reactors (AD-R1-R2-R3-R4-R5-R6) arranged in two trains (train 1: AD-R1-R2-R3 and train2: AD-R4-R5-R6) with an inner floor area of 8m x 23m and an internal height of 5m. However, the biomass must not exceed 4 m to store accumulated gases and avoid an increase in internal pressure. Fermentation chambers are built in concrete and are gas tight to prevent oxygen infiltration and biogas leakage. An in-floor heating system maintains the chamber at a constant temperature of 35-40°C. After the reactors are loaded, doors are closed and sealed, and the mixtures are kept inside for approximately 30 days. Biomass is fermented and biogas is produced. When biogas production is ended, air concentration inside the reactors is continuously measured to ensure that the reactors are not opened before all the biogas is drawn and safe levels of CO2 and H2S are reached.

The stability of the fermentation process is improved by the recirculation of percolate. In the reactors, the ceilings are equipped with sprinkles to spray the biomass with heated percolate (train 1: 32,33,34 and train 2: 35,36,37). This percolate inoculates the mixture, keeping its moisture in more than 70%. Percolate recirculation helps in both acidogenesis and methanogenesis. Percolate is collected from the chambers floor through stainless steel gutters with grating (train 1: 22,23,24 and train 2: 25,27,27). Then, the percolate (28,29) is routed to the percolate tanks (AD-T6 and AD-T7). The percolate tanks (AD-T6 and AD-T7) are equipped with inlet pipe end, filling level sensors to switch the pumps, transfer pumps with pipes to the chamber sprinkling system, heating through walls, temperature and pressure sensors, access doors, and a connection to a fermentation chamber. Percolate tanks are heated through heat exchangers (AD-E1 and AD-E2) using warm water (110,112). The capacity of percolate tanks is estimated considering the possibility of adding excess water or a different source of inoculum for start-up. Percolate is pumped to each individual reactor through HDPE pipes connected to the sprinkling unit. If the percolate level is too high, excess percolate (69,70) is sent to the effluent tank (E-T1). Warm water (106) is used to maintain the temperature in the reactors through the floor heating system. Water (107, 110) is sent to the heat exchangers AD-E3 and AD-E4, water is heated and channelled to the reactors (108, 111) and then recirculated to heating (109,112).

The biogas produced during fermentation (train 1: 14,15,16 and train 2: 17,18,19) is extracted from the reactors with an explosion and leak proof ventilation system and collected through stainless-steel pipes with gas storage bags located above the reactors (AD-T4 and AD-T5). Gas composition is measured with a gas analysis device. The resulting biogas from each reactor will have different methane contents. However, streams from each reaction train (20,21) will be mixed (22) and resulting biogas will have an average methane concentration (around 54% is aspired). The moist from the biogas is removed in the storage tanks (AD-T4 and AD-T5) by passive condensation extraction, water in the gas is condensed while cooling to ambient temperature and is transferred though a water duct to the reactor chambers (train 1:63,64,65 and train 2: 66,67,68). Biogas is also produced in the percolate tanks; each tank has a connection in the ceiling to a reactor (61,62) and biogas is exhausted. Biogas from anaerobic digestion reactors (77) is sent to the gas engine (P-GE1) through a gas compressor (E-K1). Compressed biogas (95) is combined with air (79) and sent to the gas engine to produce power (78). The electricity produced by the engine is fed into the national grid and used for internal consumption.

During the fermentation process, a solid digestate is produced (train 1: 38, 39, 40 and train 2: 41,42,43). A part of the digestate (train 1: 44, 45,46 and train 2: 47,48,49) is sent to the storage bay (A-T3) and mixed with fresh materials to be used as inoculum. The remaining digestate (train 1: 50,51,52 and train 2: 53,54,55) from individual chambers is (56) mechanically fed to compost reactors (C-R1-R2-R3) by mechanical front loaders (80, 81, 82). In compost reactors a continuous supply of air is needed (87,88,89) to maintain the digestate for at least 15 days at 55°C. Air from compost reactors (90,91,92) is collected (93) and sent to the biotrickling filter E-FIL1. Solid fertilizer from each compost reactor (83,84,85) is sent to stabilization (86). Stabilization is performed in a fertilizer storage bay C-A4 in which solid material is cooled to ambient temperature. Stabilized fertilizer (104) is sent to the fertilizer shredder (C-M1) and sent to packing (106).

The complete facility has a ventilation system that provides enough ventilation for the fermenter charging and discharging process. The exhaust air from the chambers and storage bay (76), and compost air (93) is discharged to the atmosphere via a biotrickling filter E-FIL1. Gases for cleaning (96) are sent to the filter by the biotrickling filter fan (E-E1). The biotrickling filter uses synthetic materials on which degrading bacteria are immobilized as biofilms. The contaminated air flows through the media bed and the active biofilms degrades odorous compounds. A stream of water (103) needs to be continuously recirculated to pass through the media, making the bed biologically active. Scrubbing water (99) is sent to water treatment, and sludge (100) from the filter to solid management. When makeup water is needed (101), water is sent to the biotrickling water storage tank (E-T2) and pumped to the filter. Clean gas is discharged to the atmosphere (97). Liquid effluents from different parts of the process are collected (75) and sent to the effluents tank E-T1 to further treatment (106) in an industrial water treatment plant.

Finally, the waste management facility will have supervisory control and data acquisition (SCADA), and the entire plant will be automated by PLC. A compressor that produces the necessary compressed air to supply all the pneumatic valves. In an event that needs an emergency stop, pneumatic valves are depressurized automatically. Reactor doors are pneumatically closed during the fermentation process. To open the chambers the control system will give an approval only when concentrations of <3% CH4, <0.5% of CO2 and >18% of oxygen are measured. Pneumatic doors on reactors can be opened only with a key. Percolate recirculation systems are also monitored by the control system. Percolate tanks will be equipped with level alarms. Additionally, biogas quantity and quality, temperature, pressure in anaerobic digestion, compost reactors, and biogas tanks, percolate quantities, valve and plant conditions are continuously monitored via the PLC. In biogas storage tanks, internal pressure must not exceed 25 mbar to ensure safe conditions. Pressure control in storage tanks is carried out with mechanical pressure relief valves that direct the excess biogas to a flare. Biogas storage tanks can be loaded only to a maximum of 40% of capacity, this is performed by a level control sensor.

2. Scenario 2 (SC2): three dry AD facilities for Sabana Centro

The dry anaerobic digestion facility receives stackable OFMSW and MGW with high total solids (>20%). MGW is used as a co-substrate to mitigate negative effects of undesirable materials, according to the results of laboratory and pilot scale experiments a 50/50 weight ratio is recommended. In this facility organics are mixed and sent to garage type, gas tight, concrete reactors (fermentation chambers or digesters) using a mechanical loading shovel with no pre-processing required. This plant contemplates percolate recirculation to maintain biomass activity through an external percolate storage system. The fermentation process occurs in the range of 35-40°C and biogas is produced, stored and sent to use as fuel in a combustion engine to produce electricity. Batch operation mode was considered first due to the modularity of the system, this allows to increase amounts of materials to manage by additional fermenters. According to experiences of biogas producers from the UK, the minimum number of reactors is three, to ensure biogas availability to feed the engine.

The process starts with the reception of OFSMW and MGW at the receiving bay (AD-1), both substrates are transported to the facility by collection trucks (1,2). At the receiving bay, useless waste is manually separated (5) and sent to the others collection bin (AD-T1), to be stored and sent to landfills by collection trucks once a week (41). Screened waste (3) is sent to manual sorting (AD-2) in which operators separate manually recyclables (6) such as glass, plastics, metal, and paper. Recyclable materials are sent to the recyclables bin (AD-T2) and stored to be collected by waste collectors from Sabana Centro (40). Receiving of waste (AD-1) and manual sorting processes (AD-2) are performed in the same area of the plant. OFMSW and MGW are assumed to be delivered on different days of the week. However, the receiving and manual sorting area were designed to have enough capacity to receive both at the same time. Rich organic fraction (4) is sent to the storage bay (AD-T3) in which substrates are mixed and stored until a fermentation chamber is available. The storage bay is equipped with extractors in the ceiling and leachate collection pipes. Once a fermentation chamber is available, mixed organics are sent to anaerobic digestion (7). The supply of biomass to the reactors is performed every 28-35 days. To ensure biogas and methane productivity, the feeding of reactors requires the extraction of partially fermented material within the chamber. A portion of extracted biomass is used as inoculum (26,27,28), sent to the storage bay (AD-T3) and mixed with fresh substrates in an approximate ratio of 45/55 using a front loader. This ratio may be adjusted to accommodate possible variations in the substrate composition. The total mixture (8,9,10) is sent to bioreactors (AD-R1-R2-R3).

The plant is equipped by six anaerobic reactors (AD-R1-R2-R3) with an inner floor area of 8m x 23m and an internal height of 5m. However, the biomass must not exceed 4 m to store accumulated gases and avoid an increase in internal pressure. Fermentation chambers are built in concrete and are gas tight to prevent oxygen infiltration and biogas leakage. An in-floor heating system maintains the chamber at a constant temperature of 35-40°C. After the reactors are loaded, doors are closed and sealed, and the mixtures are kept inside for approximately 30 days. Biomass is fermented and biogas is produced. When biogas production is ended, air concentration inside the reactors is continuously measured to ensure that the reactors are not opened before all the biogas is drawn and safe levels of CO2 and H2S are reached.

The stability of the fermentation process is improved by the recirculation of percolate. In the reactors, the ceilings are equipped with sprinkles to spray the biomass with heated percolate (20,21,22). This percolate inoculates the mixture, keeping its moisture in more than 70%. Percolate recirculation helps in both acidogenesis and methanogenesis. Percolate is collected from the chambers floor through stainless steel gutters with grating (15,16,17). Then, the percolate (19) is routed to the percolate tanks (AD-T5). The percolate tank (AD-T5) is equipped with inlet pipe end, filling level sensors to switch the pumps, transfer pumps with pipes to the chamber sprinkling system, heating through walls, temperature and pressure sensors, access doors, and a connection to a fermentation chamber. Percolate tanks are heated through heat exchangers (AD-E1) using warm water (). The capacity of percolate tanks is estimated considering the possibility of adding excess water or a different source of inoculum for start-up. Percolate is pumped to each individual reactor through HDPE pipes connected to the sprinkling unit. If the percolate level is too high, excess percolate (69,70) is sent to the effluent tank (E-T1). Warm water (106) is used to maintain the temperature in the reactors through the floor heating system. Water (107, 110) is sent to the heat exchangers AD-E3 and AD-E4, water is heated and channelled to the reactors (108, 111) and then recirculated to heating (109,112).

The biogas produced during fermentation (train 1: 14,15,16 and train 2: 17,18,19) is extracted from the reactors with an explosion and leak proof ventilation system and collected through stainless-steel pipes with gas storage bags located above the reactors (AD-T4 and AD-T5). Gas composition is measured with a gas analysis device. The resulting biogas from each reactor will have different methane contents. However, streams from each reaction train (20,21) will be mixed (22) and resulting biogas will have an average methane concentration (around 54% is aspired). The moist from the biogas is removed in the storage tanks (AD-T4 and AD-T5) by passive condensation extraction, water in the gas is condensed while cooling to ambient temperature and is transferred though a water duct to the reactor chambers (train 1:63,64,65 and train 2: 66,67,68). Biogas is also produced in the percolate tanks; each tank has a connection in the ceiling to a reactor (61,62) and biogas is exhausted. Biogas from anaerobic digestion reactors (77) is sent to the gas engine (P-GE1) through a gas compressor (E-K1). Compressed biogas (95) is combined with air (79) and sent to the gas engine to produce power (78). The electricity produced by the engine is fed into the national grid and used for internal consumption.

During the fermentation process, a solid digestate is produced (train 1: 38, 39, 40 and train 2: 41,42,43). A part of the digestate (train 1: 44, 45,46 and train 2: 47,48,49) is sent to the storage bay (A-T3) and mixed with fresh materials to be used as inoculum. The remaining digestate (train 1: 50,51,52 and train 2: 53,54,55) from individual chambers is (56) mechanically fed to compost reactors (C-R1-R2-R3) by mechanical front loaders (80, 81, 82). In compost reactors a continuous supply of air is needed (87,88,89) to maintain the digestate for at least 15 days at 55°C. Air from compost reactors (90,91,92) is collected (93) and sent to the biotrickling filter E-FIL1. Solid fertilizer from each compost reactor (83,84,85) is sent to stabilization (86). Stabilization is performed in a fertilizer storage bay C-A4 in which solid material is cooled to ambient temperature. Stabilized fertilizer (104) is sent to the fertilizer shredder (C-M1) and sent to packing (106).

The complete facility has a ventilation system that provides enough ventilation for the fermenter charging and discharging process. The exhaust air from the chambers and storage bay (76), and compost air (93) is discharged to the atmosphere via a biotrickling filter E-FIL1. Gases for cleaning (96) are sent to the filter by the biotrickling filter fan (E-E1). The biotrickling filter uses synthetic materials on which degrading bacteria are immobilized as biofilms. The contaminated air flows through the media bed and the active biofilms degrades odorous compounds. A stream of water (103) needs to be continuously recirculated to pass through the media, making the bed biologically active. Scrubbing water (99) is sent to water treatment, and sludge (100) from the filter to solid management. When makeup water is needed (101), water is sent to the biotrickling water storage tank (E-T2) and pumped to the filter. Clean gas is discharged to the atmosphere (97). Liquid effluents from different parts of the process are collected (75) and sent to the effluents tank E-T1 to further treatment (106) in an industrial water treatment plant.

Finally, the waste management facility will have supervisory control and data acquisition (SCADA), and the entire plant will be automated by PLC. A compressor that produces the necessary compressed air to supply all the pneumatic valves. In an event that needs an emergency stop, pneumatic valves are depressurized automatically. Reactor doors are pneumatically closed during the fermentation process. To open the chambers the control system will give an approval only when concentrations of <3% CH4, <0.5% of CO2 and >18% of oxygen are measured. Pneumatic doors on reactors can be opened only with a key. Percolate recirculation systems are also monitored by the control system. Percolate tanks will be equipped with level alarms. Additionally, biogas quantity and quality, temperature, pressure in anaerobic digestion, compost reactors, and biogas tanks, percolate quantities, valve and plant conditions are continuously monitored via the PLC. In biogas storage tanks, internal pressure must not exceed 25 mbar to ensure safe conditions. Pressure control in storage tanks is carried out with mechanical pressure relief valves that direct the excess biogas to a flare. Biogas storage tanks can be loaded only to a maximum of 40% of capacity, this is performed by a level control sensor.

3. Scenario Cajicá: one small-scale plant for Cajicá

The dry anaerobic digestion facility receives stackable OFMSW and MGW with high total solids (>20%). MGW is used as a co-substrate to mitigate negative effects of undesirable materials, according to the results of laboratory and pilot scale experiments a 50/50 weight ratio is recommended. In this facility organics are mixed and sent to garage type, gas tight, concrete reactors (fermentation chambers or digesters) using a mechanical loading shovel with no pre-processing required. This plant contemplates percolate recirculation to maintain biomass activity through an external percolate storage system. The fermentation process occurs in the range of 35-40°C and biogas is produced, stored and sent to use as fuel in a combustion engine to produce electricity. Batch operation mode was considered first due to the modularity of the system, this allows to increase amounts of materials to manage by additional fermenters. According to experiences of biogas producers from the UK, the minimum number of reactors is three, to ensure biogas availability to feed the engine.

The process starts with the reception of OFSMW and MGW at the receiving bay (AD-1), both substrates are transported to the facility by collection trucks (1,2). At the receiving bay, useless waste is manually separated (5) and sent to the others collection bin (AD-T1), to be stored and sent to landfills by collection trucks once a week (41). Screened waste (3) is sent to manual sorting (AD-2) in which operators separate manually recyclables (6) such as glass, plastics, metal, and paper. Recyclable materials are sent to the recyclables bin (AD-T2) and stored to be collected by waste collectors from Sabana Centro (40). Receiving of waste (AD-1) and manual sorting processes (AD-2) are performed in the same area of the plant. OFMSW and MGW are assumed to be delivered on different days of the week. However, the receiving and manual sorting area were designed to have enough capacity to receive both at the same time. Rich organic fraction (4) is sent to the storage bay (AD-T3) in which substrates are mixed and stored until a fermentation chamber is available. The storage bay is equipped with extractors in the ceiling and leachate collection pipes. Once a fermentation chamber is available, mixed organics are sent to anaerobic digestion (7). The supply of biomass to the reactors is performed every 28-35 days. To ensure biogas and methane productivity, the feeding of reactors requires the extraction of partially fermented material within the chamber. A portion of extracted biomass is used as inoculum (26,27,28), sent to the storage bay (AD-T3) and mixed with fresh substrates in an approximate ratio of 45/55 using a front loader. This ratio may be adjusted to accommodate possible variations in the substrate composition. The total mixture (8,9,10) is sent to bioreactors (AD-R1-R2-R3).

The plant is equipped by six anaerobic reactors (AD-R1-R2-R3) with an inner floor area of 8m x 23m and an internal height of 5m. However, the biomass must not exceed 4 m to store accumulated gases and avoid an increase in internal pressure. Fermentation chambers are built in concrete and are gas tight to prevent oxygen infiltration and biogas leakage. An in-floor heating system maintains the chamber at a constant temperature of 35-40°C. After the reactors are loaded, doors are closed and sealed, and the mixtures are kept inside for approximately 30 days. Biomass is fermented and biogas is produced. When biogas production is ended, air concentration inside the reactors is continuously measured to ensure that the reactors are not opened before all the biogas is drawn and safe levels of CO2 and H2S are reached.

The stability of the fermentation process is improved by the recirculation of percolate. In the reactors, the ceilings are equipped with sprinkles to spray the biomass with heated percolate (20,21,22). This percolate inoculates the mixture, keeping its moisture in more than 70%. Percolate recirculation helps in both acidogenesis and methanogenesis. Percolate is collected from the chambers floor through stainless steel gutters with grating (15,16,17). Then, the percolate (19) is routed to the percolate tanks (AD-T5). The percolate tank (AD-T5) is equipped with inlet pipe end, filling level sensors to switch the pumps, transfer pumps with pipes to the chamber sprinkling system, heating through walls, temperature and pressure sensors, access doors, and a connection to a fermentation chamber. Percolate tanks are heated through heat exchangers (AD-E1) using warm water (). The capacity of percolate tanks is estimated considering the possibility of adding excess water or a different source of inoculum for start-up. Percolate is pumped to each individual reactor through HDPE pipes connected to the sprinkling unit. If the percolate level is too high, excess percolate (69,70) is sent to the effluent tank (E-T1). Warm water (106) is used to maintain the temperature in the reactors through the floor heating system. Water (107, 110) is sent to the heat exchangers AD-E3 and AD-E4, water is heated and channelled to the reactors (108, 111) and then recirculated to heating (109,112).

The biogas produced during fermentation (train 1: 14,15,16 and train 2: 17,18,19) is extracted from the reactors with an explosion and leak proof ventilation system and collected through stainless-steel pipes with gas storage bags located above the reactors (AD-T4 and AD-T5). Gas composition is measured with a gas analysis device. The resulting biogas from each reactor will have different methane contents. However, streams from each reaction train (20,21) will be mixed (22) and resulting biogas will have an average methane concentration (around 54% is aspired). The moist from the biogas is removed in the storage tanks (AD-T4 and AD-T5) by passive condensation extraction, water in the gas is condensed while cooling to ambient temperature and is transferred though a water duct to the reactor chambers (train 1:63,64,65 and train 2: 66,67,68). Biogas is also produced in the percolate tanks; each tank has a connection in the ceiling to a reactor (61,62) and biogas is exhausted. Biogas from anaerobic digestion reactors (77) is sent to the gas engine (P-GE1) through a gas compressor (E-K1). Compressed biogas (95) is combined with air (79) and sent to the gas engine to produce power (78). The electricity produced by the engine is fed into the national grid and used for internal consumption.

During the fermentation process, a solid digestate is produced (train 1: 38, 39, 40 and train 2: 41,42,43). A part of the digestate (train 1: 44, 45,46 and train 2: 47,48,49) is sent to the storage bay (A-T3) and mixed with fresh materials to be used as inoculum. The remaining digestate (train 1: 50,51,52 and train 2: 53,54,55) from individual chambers is (56) mechanically fed to compost reactors (C-R1-R2-R3) by mechanical front loaders (80, 81, 82). In compost reactors a continuous supply of air is needed (87,88,89) to maintain the digestate for at least 15 days at 55°C. Air from compost reactors (90,91,92) is collected (93) and sent to the biotrickling filter E-FIL1. Solid fertilizer from each compost reactor (83,84,85) is sent to stabilization (86). Stabilization is performed in a fertilizer storage bay C-A4 in which solid material is cooled to ambient temperature. Stabilized fertilizer (104) is sent to the fertilizer shredder (C-M1) and sent to packing (106).

The complete facility has a ventilation system that provides enough ventilation for the fermenter charging and discharging process. The exhaust air from the chambers and storage bay (76), and compost air (93) is discharged to the atmosphere via a biotrickling filter E-FIL1. Gases for cleaning (96) are sent to the filter by the biotrickling filter fan (E-E1). The biotrickling filter uses synthetic materials on which degrading bacteria are immobilized as biofilms. The contaminated air flows through the media bed and the active biofilms degrades odorous compounds. A stream of water (103) needs to be continuously recirculated to pass through the media, making the bed biologically active. Scrubbing water (99) is sent to water treatment, and sludge (100) from the filter to solid management. When makeup water is needed (101), water is sent to the biotrickling water storage tank (E-T2) and pumped to the filter. Clean gas is discharged to the atmosphere (97). Liquid effluents from different parts of the process are collected (75) and sent to the effluents tank E-T1 to further treatment (106) in an industrial water treatment plant.

Finally, the waste management facility will have supervisory control and data acquisition (SCADA), and the entire plant will be automated by PLC. A compressor that produces the necessary compressed air to supply all the pneumatic valves. In an event that needs an emergency stop, pneumatic valves are depressurized automatically. Reactor doors are pneumatically closed during the fermentation process. To open the chambers the control system will give an approval only when concentrations of <3% CH4, <0.5% of CO2 and >18% of oxygen are measured. Pneumatic doors on reactors can be opened only with a key. Percolate recirculation systems are also monitored by the control system. Percolate tanks will be equipped with level alarms. Additionally, biogas quantity and quality, temperature, pressure in anaerobic digestion, compost reactors, and biogas tanks, percolate quantities, valve and plant conditions are continuously monitored via the PLC. In biogas storage tanks, internal pressure must not exceed 25 mbar to ensure safe conditions. Pressure control in storage tanks is carried out with mechanical pressure relief valves that direct the excess biogas to a flare. Biogas storage tanks can be loaded only to a maximum of 40% of capacity, this is performed by a level control sensor.

Appendix III

Process Flow Diagrams for the dry anaerobic digestion production scenarios

In this Appendix, Process Flow Diagrams are presented for the three evaluated scenarios. First, Sabana Centro 1 (SC1) in which one municipal plant will be built for the eleven municipalities. Then, Sabana Centro 2 (SC2) which considers three identical plants with the same capacity. Finally, the scenario Cajicá, in which a small-scale plant only for the municipality of Cajicá was designed

1. **Scenario 1 (SC1): one municipal dry AD facility for Sabana Centro**

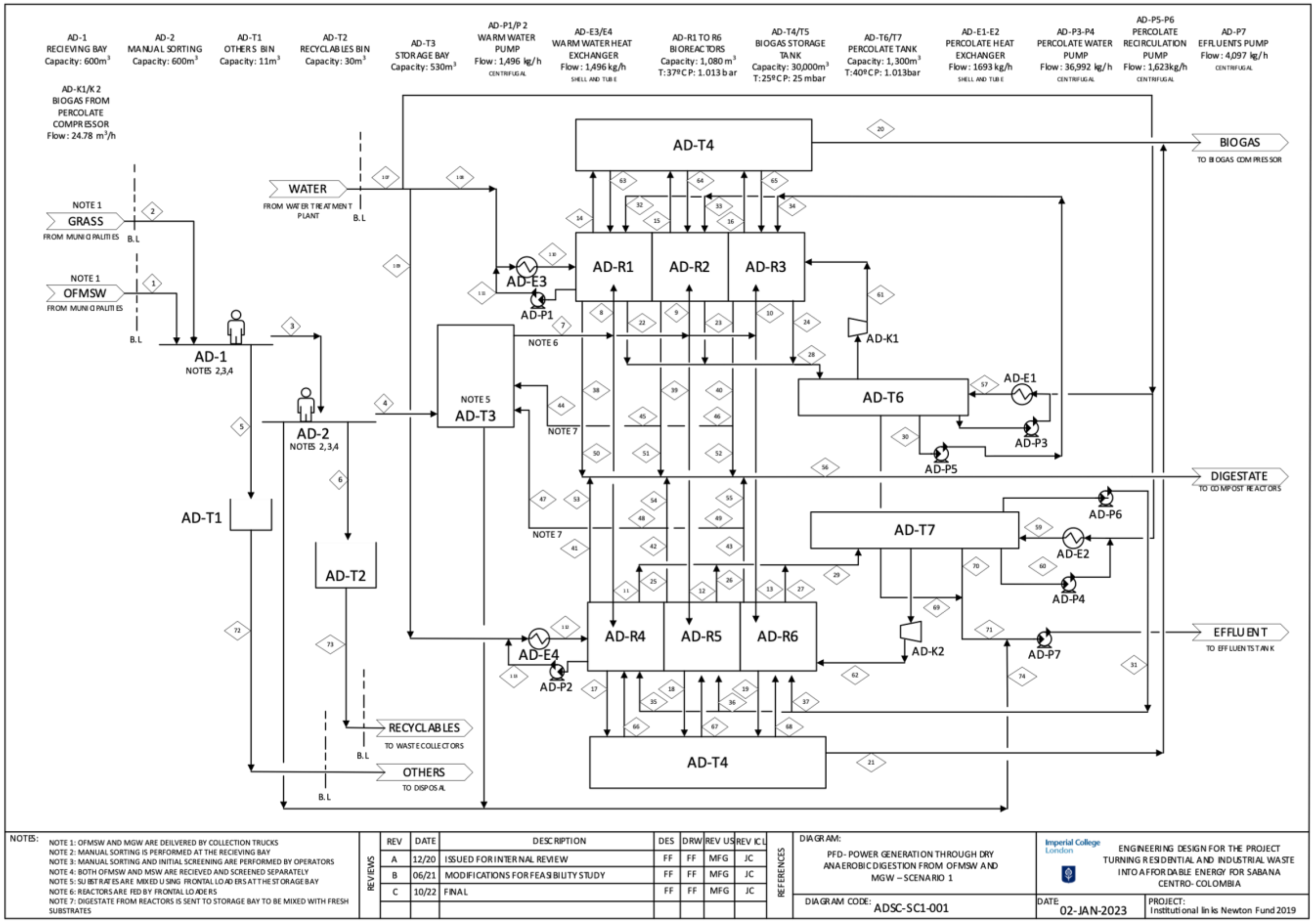
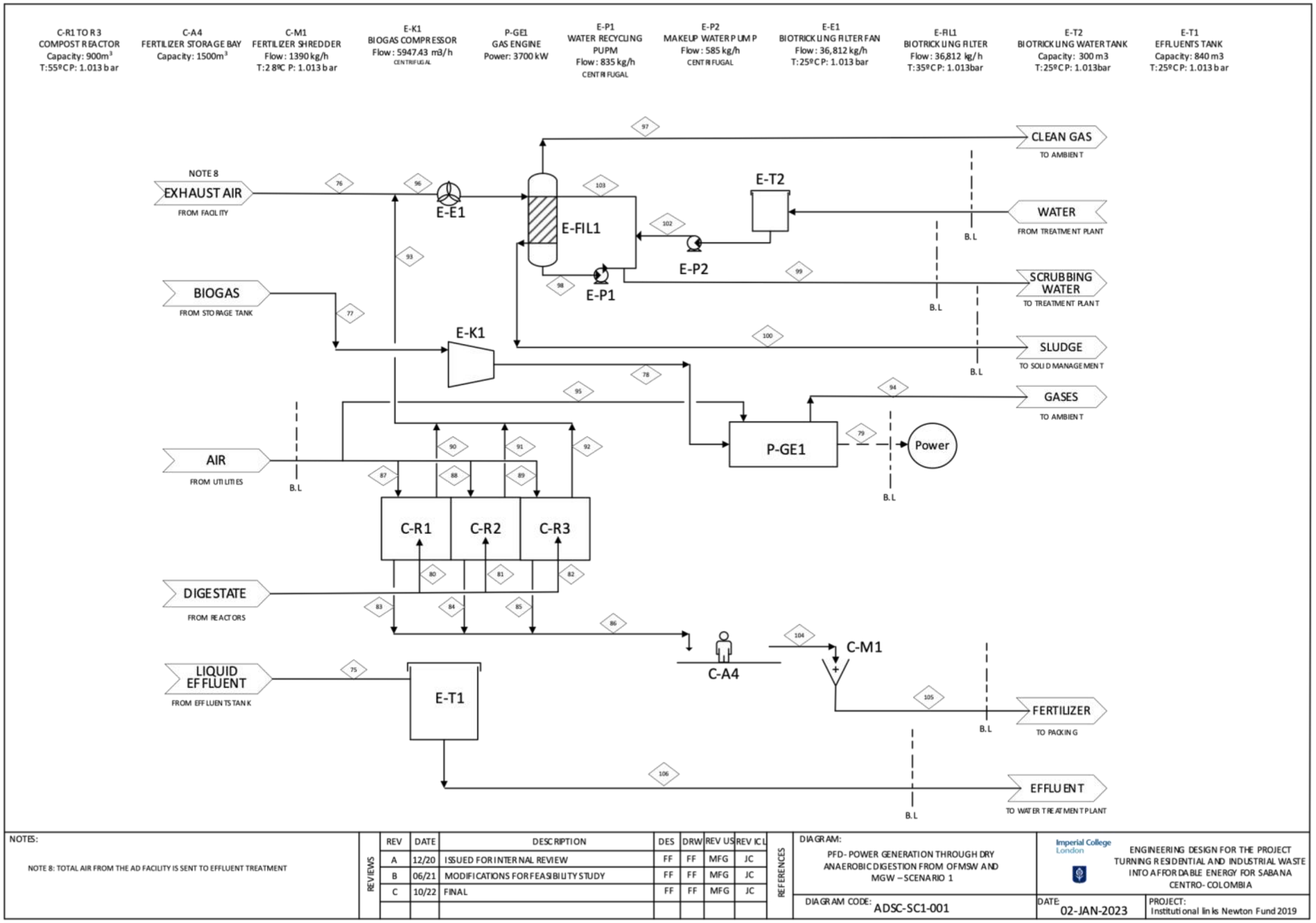


Figure 1. Process Flow Diagram for SC1-001



NOTES:

NOTE 8: TOTAL AIR FROM THE AD FACILITY IS SENT TO EFFLUENT TREATMENT

REVIEWS

REV	DATE	DESCRIPTION	DES	DRW	REV US	REV ICL
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	JC
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	JC
C	10/22	FINAL	FF	FF	MFG	JC

REFERENCES

DIAGRAM: PFD- POWER GENERATION THROUGH DRY ANAEROBIC DIGESTION FROM OFMSW AND MGW – SCENARIO 1

DIAGRAM CODE: ADSC-SC1-001

Imperial College London

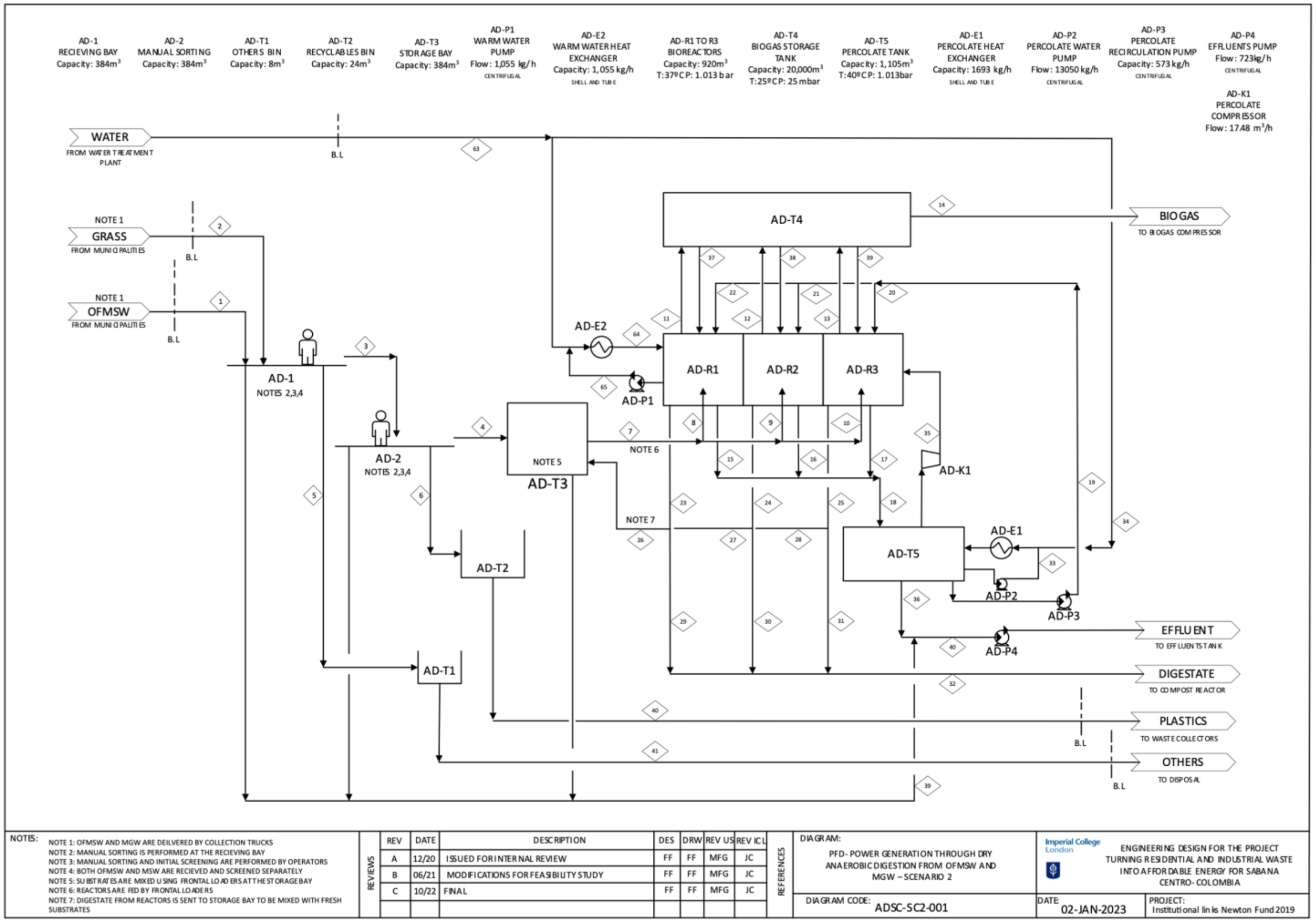
ENGINEERING DESIGN FOR THE PROJECT TURNING RESIDENTIAL AND INDUSTRIAL WASTE INTO AFFORDABLE ENERGY FOR SABANA CENTRO- COLOMBIA

DATE: 02-JAN-2023

PROJECT: Institutional links Newton Fund 2019

Figure 2. Process Flow Diagram for SC1-002

2. Scenario 2 (SC2): three dry AD facilities for Sabana Centro



NOTES:
NOTE 1: OFMSW AND MGW ARE DEILVERED BY COLLECTION TRUCKS
NOTE 2: MANUAL SORTING IS PERFORMED AT THE RECIEVING BAY
NOTE 3: MANUAL SORTING AND INITIAL SCREENING ARE PERFORMED BY OPERATORS
NOTE 4: BOTH OFMSW AND MSW ARE RECIEVED AND SCREENED SEPARATELY
NOTE 5: SUBSTRATES ARE MIXED USING FRONTAL LOADERS AT THE STORAGE BAY
NOTE 6: REACTORS ARE FED BY FRONTAL LOADERS
NOTE 7: DIGESTATE FROM REACTORS IS SENT TO STORAGE BAY TO BE MIXED WITH FRESH SUBSTRATES

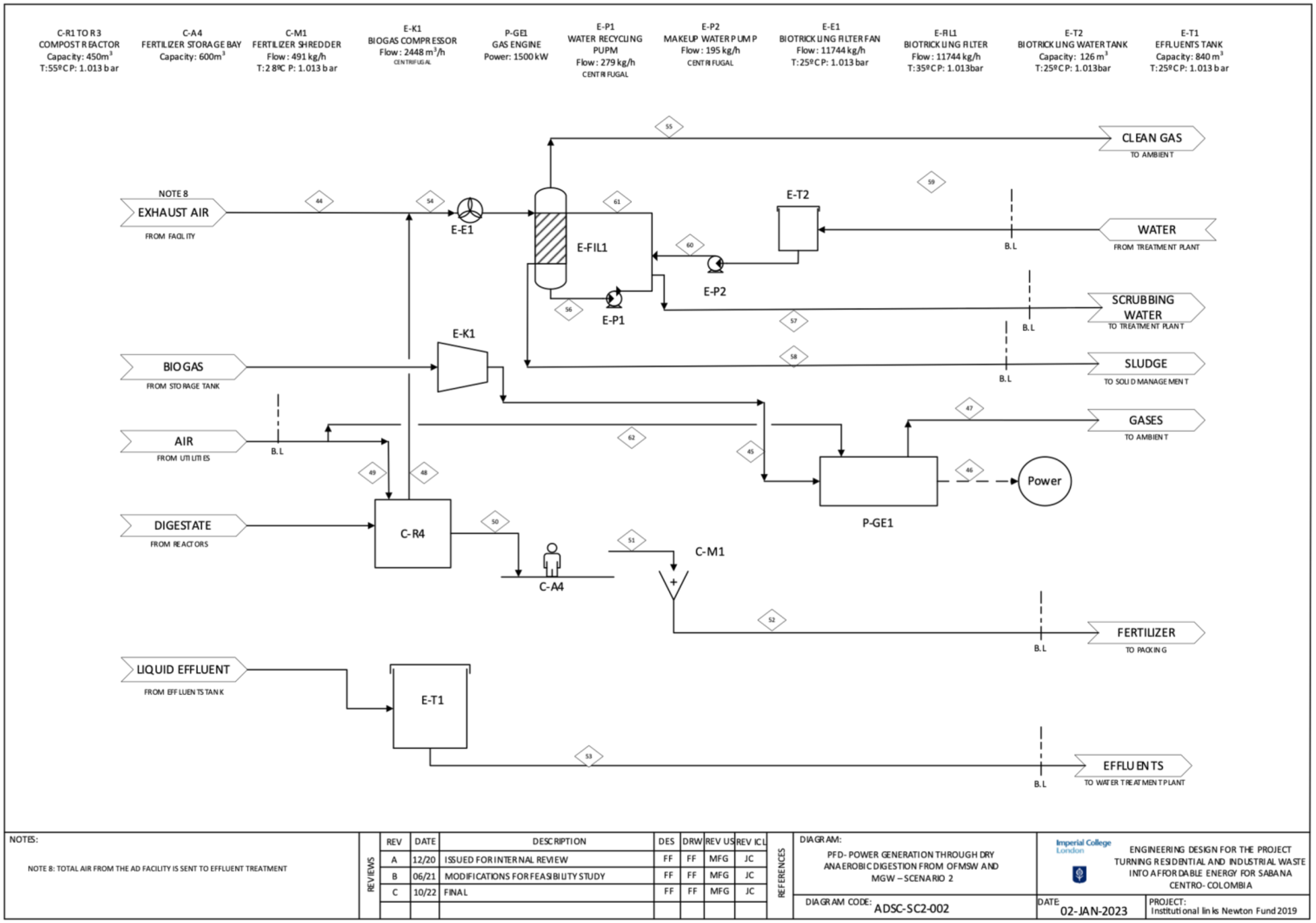
REV	DATE	DESCRIPTION	DES	DRW	REV US	REV ICL
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	JC
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	JC
C	10/22	FINAL	FF	FF	MFG	JC

DIAGRAM:
PFD- POWER GENERATION THROUGH DRY ANAEROBIC DIGESTION FROM OFMSW AND MGW – SCENARIO 2

ENGINEERING DESIGN FOR THE PROJECT TURNING RESIDENTIAL AND INDUSTRIAL WASTE INTO AFFORDABLE ENERGY FOR SABANA CENTRO- COLOMBIA

DIAGRAM CODE: ADSC-SC2-001
DATE: 02-JAN-2023
PROJECT: Institutional links Newton Fund 2019

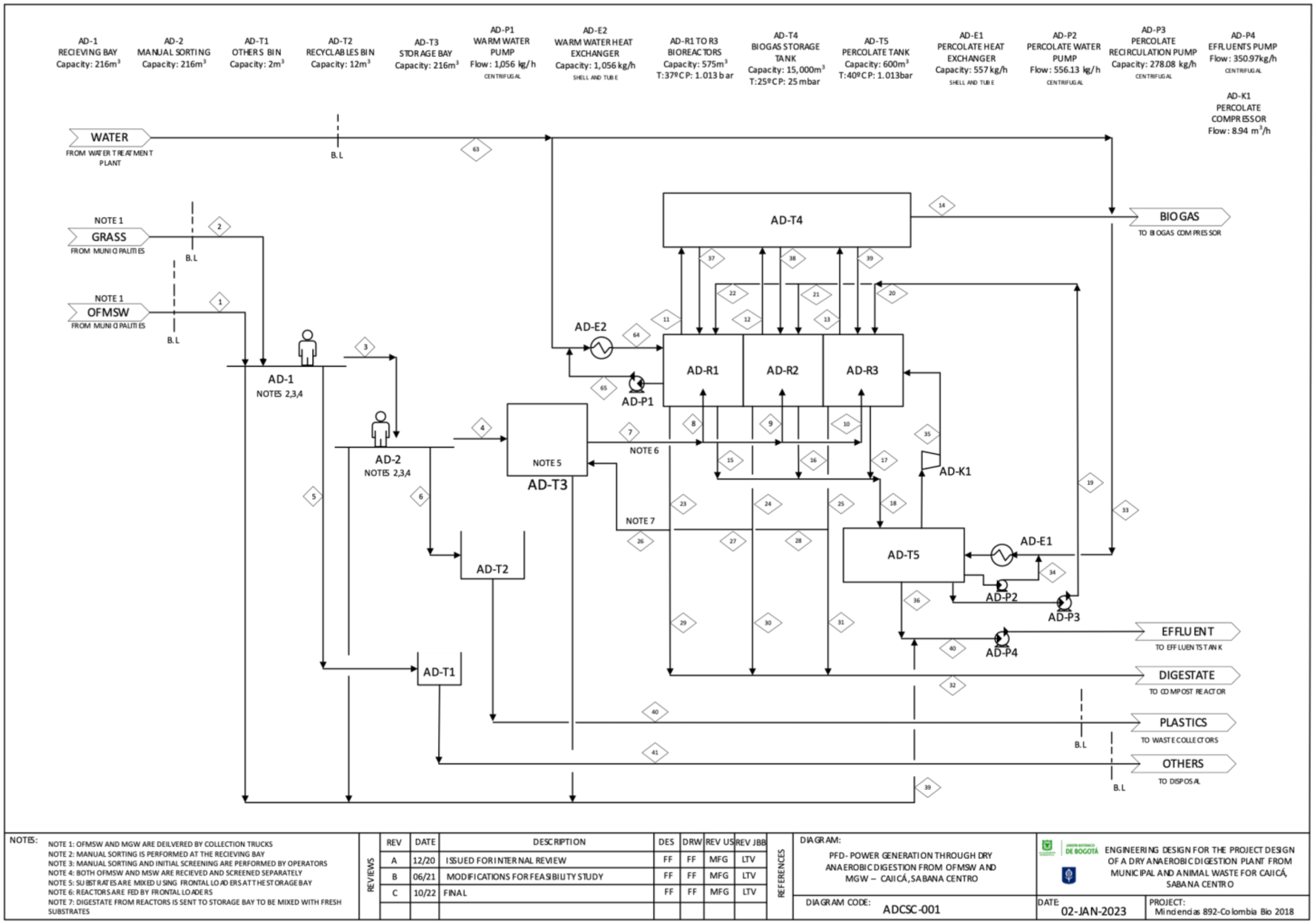
Figure 3. Process Flow Diagram for SC2-001



REV	DATE	DESCRIPTION	DES	DRW	REV US	REV ICL
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	JC
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	JC
C	10/22	FINAL	FF	FF	MFG	JC

Figure 4. Process Flow Diagram for SC2-002

3. Scenario Cajicá: one small-scale plant for Cajicá



NOTES:
NOTE 1: OFMSW AND MGW ARE DEILVERED BY COLLECTION TRUCKS
NOTE 2: MANUAL SORTING IS PERFORMED AT THE RECIEVING BAY
NOTE 3: MANUAL SORTING AND INITIAL SCREENING ARE PERFORMED BY OPERATORS
NOTE 4: BOTH OFMSW AND MSW ARE RECIEVED AND SCREENED SEPARATELY
NOTE 5: SUBSTRATES ARE MIXED USING FRONTAL LOADERS AT THE STORAGE BAY
NOTE 6: REACTORS ARE FED BY FRONTAL LOADERS
NOTE 7: DIGESTATE FROM REACTORS IS SENT TO STORAGE BAY TO BE MIXED WITH FRESH SUBSTRATES

REV	DATE	DESCRIPTION	DES	DRW	REV US	REV JBB
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	LTV
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	LTV
C	10/22	FINAL	FF	FF	MFG	LTV

DIAGRAM:
PFD- POWER GENERATION THROUGH DRY ANAEROBIC DIGESTION FROM OFMSW AND MGW – CAJICÁ, SABANA CENTRO

DIAGRAM CODE: ADCSC-001

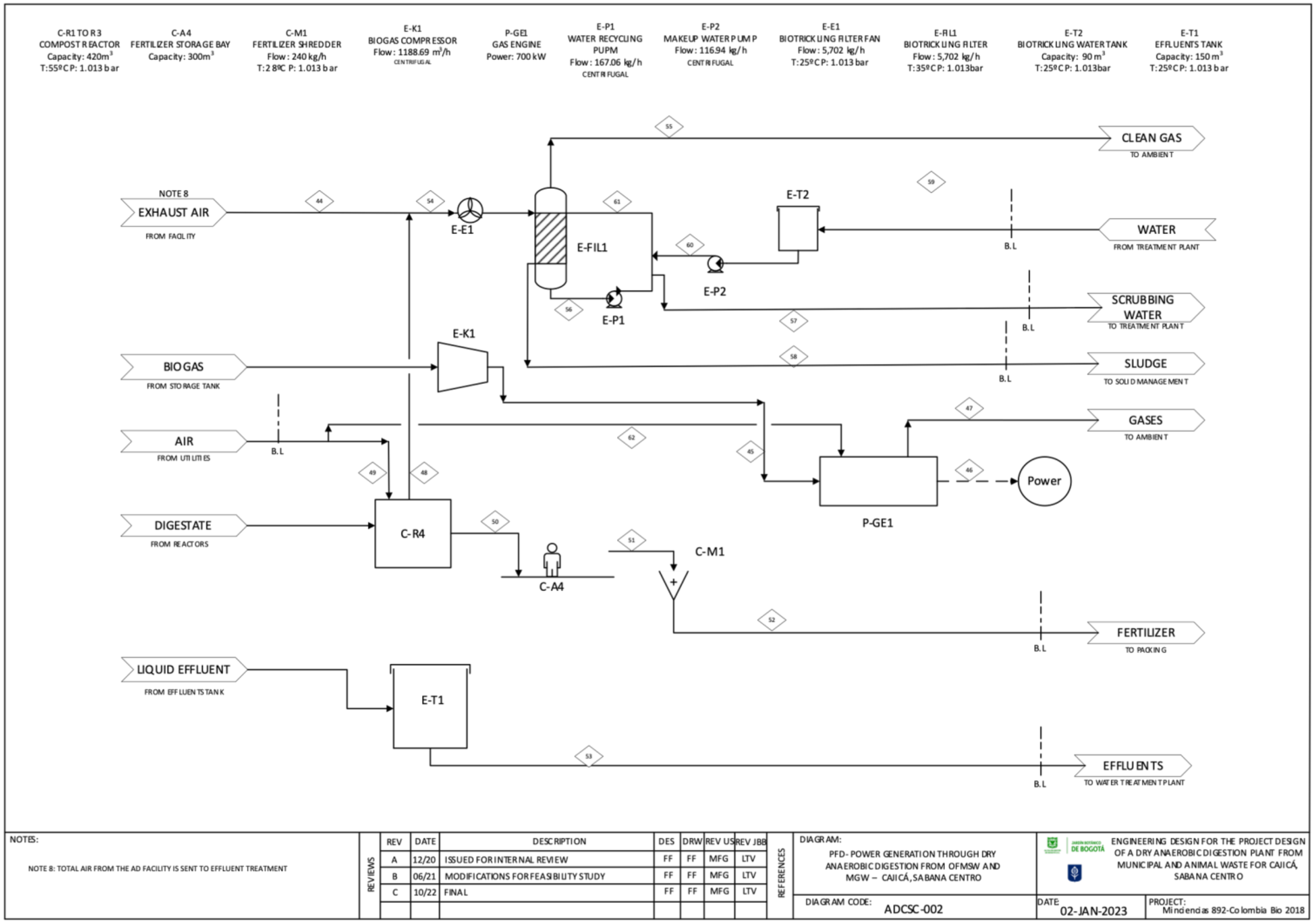
JARDÍN BOTÁNICO DE BOGOTÁ

ENGINEERING DESIGN FOR THE PROJECT DESIGN OF A DRY ANAEROBIC DIGESTION PLANT FROM MUNICIPAL AND ANIMAL WASTE FOR CAJICÁ, SABANA CENTRO

DATE: 02-JAN-2023

PROJECT: Minciencias 892-Colombia Bio 2018

Figure 5. Process Flow Diagram for CSC-001



REV	DATE	DESCRIPTION	DES	DRW	REV US	REV JBB
A	12/20	ISSUED FOR INTERNAL REVIEW	FF	FF	MFG	LTV
B	06/21	MODIFICATIONS FOR FEASIBILITY STUDY	FF	FF	MFG	LTV
C	10/22	FINAL	FF	FF	MFG	LTV

Figure 6. Process Flow Diagram for CSC-002

Appendix IV

Equipment list for the dry anaerobic digestion production scenarios

In this Appendix, the list of equipment needed in the plant is presented for the three evaluated scenarios. First, Sabana Centro 1 (SC1) in which one municipal plant will be built for the eleven municipalities (Table 1). Then, Sabana Centro 2 (SC2) which considers three identical plants with the same capacity (Table 2). Finally, the scenario Cajicá, in which a small-scale plant only for the municipality of Cajicá was designed (Table 3).

1. **Scenario 1 (SC1): one municipal dry AD facility for Sabana Centro**

Table 1. Equipment list for scenario 1 (SC1)

Name	TAG	Capacity	Operating requirements	Diagram
Receiving Bay	AD-A1	A concrete bay: 4m (H) x 12m (L) x 8m (W) Capacity: 384 m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC2-001
Manual Sorting	AD-A2		T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC2-001
Others collection bin	AD-T1	Skip bin: 2,5 m (L) x 2 m (W) and 2 m (H) Capacity: 8 m^3	T=20ºC and P=1.013 bar	ADSC-SC2-001
Recyclables collection bin	AD-T2	Recyclables concrete bay: 4m (L) x 3m (W) and 2 m (H) Capacity: 24 m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC2-001
Organics storage bay	AD-T3	A concrete bay with ceiling and underground leachate collection tubes: 4m (H) x 12m (L) x 8m(W) Capacity: 384 m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC2-001

Dry anaerobic digester	AD-R1/R2/R3	Concrete fermentation chambers 23m (L) x 8m (W) and 5m (H) Total capacity: 2760 m^3, 920 m^3 each	T= 37-40ºC P=1.013 bar	ADSC-SC2-001
Biogas storage unit	AD-T4	Total capacity: 20000 m^3	T= 25ºC P=25mbar	ADSC-SC2-001
Percolate tank	AD-T6	Stainless steel 2m (H) x 8m (L) x 69m (W) Capacity: 1105 m^3	T= 37-40ºC P=1.013 bar	ADSC-SC2-001
Percolate recirculation pump	AD-P3	Flow: 572.67 kg/h	T= 37-40ºC P=1.013 bar	ADSC-SC2-001
Percolate heat exchanger	AD-E1	Flow: 1693.08 kg/h	T= 37-40ºC P=1.013 bar	ADSC-SC2-001
Percolate water pump	AD-P2	Flow: 13051 kg/h each	T=57ºC	ADSC-SC2-001
Percolate biogas compressor	AD-K1	Flow: 17.48 m^3/h	T= 37-40ºC P= 1.5 bar	ADSC-SC2-001
Warm water heat exchanger	AD-E3	Flow: 1055.88 kg/h	T= 85ºC avg P=1.013 bar	ADSC-SC2-001
Warm water pump	AD-P1	Flow: 1055.88 kg/h	T=57ºC	ADSC-SC2-001
Compost reactor	C-R1	Stainless steel compost reactors: 5m (H) x 10m (L) x 9m (W) Total capacity: 450 m^3	T= 55ºC P= 1 bar	ADSC-SC2-002
Biogas compressor	E-K1	Flow: 2447.95 m^3/h	T= 25-50ºC	ADSC-SC2-002
Fertilizer storage bay	C-A4	A concrete bay with ceiling: 12m (H) x 10m (L) x 5m (W) Capacity: 600m^3	T=20ºC and P=1.013 bar	ADSC-SC2-002

Fertilizer shredder	C-M1	Flow: 491 kg/h	T=20ºC and P=1.013 bar	ADSC-SC2-002
Biotrickling filter	E-FIL1	Flow: 11744 kg/h	T=20ºC and P=1.013 bar	ADSC-SC2-002
Biotrickling filter fan	E-E1	Flow: 11744 kg/h	T=20ºC and P=1.013 bar	ADSC-SC2-002
Biotrickling water tank	ET-2	Steel tank: 7m (L) x 6m (W) x 3m (H) Capacity: Capacity: 126 m^3	T=20ºC and P=1.013 bar	ADSC-SC2-002
Water recycling pump	E-P1	Flow: 278.43 kg/h	T=35ºC	ADSC-SC2-002
Makeup water pump	E-P2	Flow: 194.89 kg/h	T=30ºC	ADSC-SC2-002
Effluents tank	E-T1	Steel tank: 13m (L) x 8m(w) x 3m (h) Capacity: 312m^3	T=20ºC and P=1.013 bar	ADSC-SC2-002
Effluents pump	AD-P4	Capacity: 722.77kg/h	T=20ºC and P=1.013 bar	ADSC-SC2-002
Gas engine	P-GE1	Power output: 1500 kW	-	ADSC-SC2-002

2. Scenario 2 (SC2): three dry AD facilities for Sabana Centro

Table 2. Equipment list for scenario 2 (SC2)

Name	TAG	Capacity	Operating requirements	Diagram
Receiving Bay	AD-A1	A concrete bay: 4m (H) x 15m (L) x 10m (W) Capacity: 600m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC1-001
Manual Sorting	AD-A2		T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC1-001
Others collection bin	AD-T1	Skip bin: 3m (L) x 2m (W) and 2m (H) Capacity: 11 m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC1-001
Recyclables collection bin	AD-T2	Recyclables concrete bay: 4m (L) x 3m (W) and 2.5 m (H) Capacity: 30m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC1-001
Organics storage bay	AD-T3	Concrete bay with ceiling: 4m (H) x 15m (L) x 10m (W) Capacity: 530 m^3	T=20ºC and P=1.013 bar Manual operation needed	ADSC-SC1-001
Dry anaerobic digester	AD-R1/R2/R3/R4/R5/R6	Fermentation chambers: 24m (L) x 9m (W) and 5m (H) Total capacity: 6480 m^3, 1080 m^3 each	T= 37-40ºCP=1.013 bar	ADSC-SC1-001
Biogas storage unit	AD-T4/T5	Total capacity: 30000m^3	T= 25ºC P=25mbar	ADSC-SC1-001
Percolate tank	AD-T6/T7	Stainless steel 72m (w) x 9m (l) x 2m (h) Total capacity: 2600 m^3, 1300 m^3 each	T= 37-40ºC P=1.013 bar	ADSC-SC1-001

Percolate recirculation pump	AD-P5/P6	Flow: 1623.22 kg/h each	T= 37-40ºC P=1.013 bar	ADSC-SC1-001
Percolate heat exchanger	AD-E1/E2	Flow: 1693.08 kg/h each	T= 37-40ºC P=1.013 bar	ADSC-SC1-001
Percolate water pump	AD-P3/P4	Flow: 36992 kg/h each	T=57ºC	ADSC-SC1-001
Biogas from percolate compressor	AD-K1/K2	Flow: 24.78 m^3/h	T= 37-40ºC P= 1.5 bar	ADSC-SC1-001
Warm water heat exchanger	AD-E3/E4	Flow: 1496 kg/h each	T= 85ºC avg P=1.013 bar	ADSC-SC1-001
Warm water pump	AD-P1/P2	Flow: 1496 kg/h each	T=57ºC	ADSC-SC1-001
Compost reactor	C-R1/R2/R3	Stainless steel compost reactors: 9m (W) x 20m (L) x 5m (H) Total capacity: 2700m^3, 900m^3 each	T= 55ºC P= 1 bar	ADSC-SC1-002
Biogas compressor	E-K1	Capacity: 5947.43 m3/h	T= 25-30ºC	ADSC-SC1-002
Fertilizer storage bay	C-A4	A concrete bay with ceiling: 5m (H) x 20m (L) x 15m (W) Capacity: 1500 m^3	T=20ºC P=1.013 bar	ADSC-SC1-002
Fertilizer shredder	C-M1	Flow: 1390 kg/h	T=20ºC P=1.013 bar	ADSC-SC1-002
Biotrickling filter	E-FIL1	Flow: 36812 kg/h	T=35ºC P=1.013 bar	ADSC-SC1-002
Biotrickling filter fan	E-E1	Flow: 36812 kg/h	T=20ºC P=1.013 bar	ADSC-SC1-002
Biotrickling water tank	ET-2	Steel tank: 10m (L) x 10 m(W) x 3m (H) Capacity: 300 m^3	T=20ºC P=1.013 bar	ADSC-SC1-002

Water recycling pump	E-P1	Flow: 835.30 kg/h	T=35ºC	ADSC-SC1-002
Makeup water pump	E-P2	Flow: 584.71 kg/h	T=30ºC	ADSC-SC1-002
Effluent tank	E-T1	Steel tank 20m(l) x 14 m (w) x 3 m(h) Capacity: 840 m^3	T=20ºC P=1.013 bar	ADSC-SC1-002
Effluents pump	AD-P7	Capacity: 4097.39kg/h	T=20ºC P=1.013 bar	ADSC-SC1-002
Gas engine	P-GE1	Power output: 3700 kW	-	ADSC-SC1-002

3. Scenario Cajicá: one small-scale plant for Cajicá

Table 3. Equipment list for scenario Cajicá

Name	TAG	Capacity	Operating requirements	Diagram
Receiving Bay	AD-A1	A concrete bay: 4m (H) x 9m (L) x 6m (W) Capacity: 216 m^3	T=20ºC P=1.013 bar. Manual operation needed	ADCSC-001
Manual Sorting	AD-A2		T=20ºC P=1.013 bar. Manual operation needed	ADCSC-001
Others collection bin	AD-T1	Skip bin: 1m (L) x 1m (W) and 2m (H) Capacity: 2 m^3	T=20ºC P=1.013 bar. Manual operation needed	ADCSC-001
Recyclables collection bin	AD-T2	Recyclables concrete bay: 3m (L) x 3m (W) and 2m (H) Capacity: 12 m^3	T=20ºC P=1.013 bar. Manual operation needed	ADCSC-001

Organics storage bay	AD-T3	A concrete bay with ceiling and underground leachate collection tubes: 4m (H) x 9m (L) x 6m(W) Capacity: 216 m^3	T=20ºC P=1.013 bar. Manual operation needed	ADCSC-001
Dry anaerobic digester	AD-R1/R2/R3	Concrete fermentation chambers 20m (L) x 7m (W) and 3.75m (H) Total capacity: 1575m^3, 525m^3 each	T= 37-40ºC P=1.013 bar.	ADCSC-001
Biogas storage unit	AD-T4	Total capacity: 15000 m^3	T= 25ºC P=25mbar	ADCSC-001
Percolate tank	AD-T6	Stainless steel 2m (H) x 6m (L) x 50m (W) Capacity: 600 m^3	T= 37-40ºC P=1.013 bar.	ADCSC-001
Percolate recirculation pump	AD-P3	Flow: 278.08kg/h	T= 37-40ºC P=1.013 bar.	ADCSC-001
Percolate heat exchanger	AD-E1	Flow: 556.13 kg/h	T= 37-40ºC P=1.013 bar.	ADCSC-001
Percolate water pump	AD-P2	Flow: 556.13 kg/h	T=57ºC	ADCSC-001
Percolate biogas compressor	AD-K1	Flow: 8.49 m3/h	T= 37-40ºC P= 1.5 bar	ADCSC-001
Warm water heat exchanger	AD-E3	Flow: 512.71 kg/h	T= 85ºC avg P=1.013 bar.	ADCSC-001
Warm water pump	AD-P1	Flow: 1055.88 kg/h	T=57ºC	ADCSC-001
Compost reactor	C-R1	Stainless steel compost reactor: 5m (H) x 12m (L) x 7m (W) Total capacity: 420 m^3	T= 55ºC P= 1 bar	ADCSC-002

Biogas compressor	E-K1	Flow: 1188,69 m^3/h	T= 25-50ºC	ADCSC-002
Fertilizer storage bay	C-A4	A concrete bay with ceiling: 10m (H) x 6m (L) x 5m (W) Capacity: 300m^3	T=20ºC P=1.013 bar.	ADCSC-002
Fertilizer shredder	C-M1	Flow: 240 kg/h	T=20ºC P=1.013 bar.	ADCSC-002
Biotrickling filter	E-FIL1	Flow: 5702 kg/h	T=35ºC P=1.013 bar.	ADCSC-002
Biotrickling filter fan	E-E1	Flow: 5702kg/h	T=20ºC P=1.013 bar.	ADCSC-002
Biotrickling water tank	ET-2	Steel tank: 6m (L) x 5m (W) x 3m (H) Capacity: Capacity: 90 m^3	T=20ºC P=1.013 bar.	ADCSC-002
Water recycling pump	E-P1	Flow: 167.06 kg/h	T=20ºC P=1.013 bar.	ADCSC-002
Makeup water pump	E-P2	Flow: 116.94 kg/h	T=30ºC	ADCSC-002
Effluents tank	E-T1	Steel tank: 10m (L) x 5m(w) x 3m (h) Capacity: 150m^3	T=20ºC P=1.013 bar.	ADCSC-002
Effluents pump	AD-P4	Capacity: 350.97 kg/h	T=20ºC P=1.013 bar.	ADCSC-002
Gas engine	P-GE1	Power output: 700 kW	-	ADCSC-002

Appendix V

Lessons for the design of garage type dry anaerobic digestion pilot plants: the case of the Botanical Garden of Bogotá

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Summary

The present study is product of the research “Evaluation of a biogas production process from municipal solid waste for Sabana Centro, Cundinamarca using dry anaerobic digestion” developed from 2019 to 2021 and funded by the Ministry of Science, Technology, and Innovation of Colombia. Dry anaerobic digestion (AD) technology present advantages compared to wet, such as the reduced use of water and higher organic load rates. However, there are still many disadvantages that hinder its popularity around the world particularly in relation to evaluation at pilot-scale level. The present work aims to point out key lessons for the design of a dry AD plants using the only dry pilot-scale facility existing in Colombia, as a case study. The evaluation of the plant was performed by pilot scale experiments using local biomass: the Organic Fraction of Municipal Solid Waste and rumen content. During the experiments, opportunities for improvement were identified. Critical points such as airtight doors, knowledge of the physicochemical characteristics of the substrates, temperature of the process, and loading ramps were identified. Improvements in the identified critical points have the potential to support other researchers and design suitable dry AD facilities. Through this project, guidelines for pilot plant dry AD design are developed for the first time in Colombia.

Keywords: biogas, dry anaerobic digestion, garage type, pilot plant, OFMSW

1. INTRODUCTION

Municipal Solid Waste (MSW) generation is increasing globally and is mostly burnt or disposed of in landfills. In 2017, about 2.01 billion tonnes of MSW were generated globally (Panigrahi & Dubey, 2019). According to the World Bank, waste production is expected to increase from 3.5 million tons per day to 6.1 million tons per day by 2025 (Makarichi et al., 2018). When mismanaged, MSW can contribute to climate change due to the formation of methane. It also causes ecosystem damage and resource depletion (Panigrahi & Dubey, 2019). Anaerobic digestion (AD) has been applied worldwide due its capacity to degrade high volumes of organic materials (Sevillano et al., 2021). Dry AD is used to treat organic waste with high solids contents around 20% and 40%, making it suitable for the organic fraction of municipal solid waste (OFSMW) (Rocamora et al., 2020). Dry AD presents many operational advantages as compared to wet AD (Rocamora et al., 2020). However, dry AD is nowadays less popular than wet processes due to a perceived operational complexity to achieve stable production. This complexity is mainly represented by long degradation times and the potential accumulation of inhibitory compounds. Lower methane production and higher inoculation ratios can be expected when inhibitions occur (Rocamora et al., 2020).

In Colombia, few efforts are in place to retrieve the energy content of OFMSW, waste production is growing every year, and the recycling rate is only 17% of total waste (Superintendencia de Servicios Públicos Domiciliarios, 2019). However, just wet AD plants are used since dry AD have still technological hurdles. This fact highlights the relevance of overcoming the disadvantages of dry AD technologies to increase the capacity worldwide by the implementation of pilot-scale studies with local biomass. In Bogota, the capital of Colombia, a dry AD pilot plant is located at the Botanical Garden of Bogota Jose Celestino Mutis (BGB) with the aim of performing evaluation of biogas production processes using local waste. Previous experiments performed by the BGB considering food waste, animal manure and pruning waste displayed some complications during the production process. As a result, the aim of this study was to evaluate the biogas production process at the BGB pilot plant, to identify lessons that can support the design and operation of dry AD pilot plants managing OFMSW and animal waste. This evaluation was achieved during a complete year of experiments using locally provided waste.

2. MATERIALS AND METHODS

2.1 The Botanical Garden of Bogota dry AD plant

The BGB dry AD plant was built by a local provider and consist of the following elements: (1) three garage type digesters working in parallel, build in concrete with 30 cubic meters of volume each, (2) airtight doors, (3) underground tanks with 13.5 litters, (4) a trap of variable granulometry ensures the screening of the solid material inside the digesters, (5) the percolate tank with 1 cubic meter, (6) percolate recirculation system, (7) the biogas network, and (8) the percolate electrical heating system. The water is heated by a gas heater using natural gas. Figure 1 shows the block diagram of the plant.

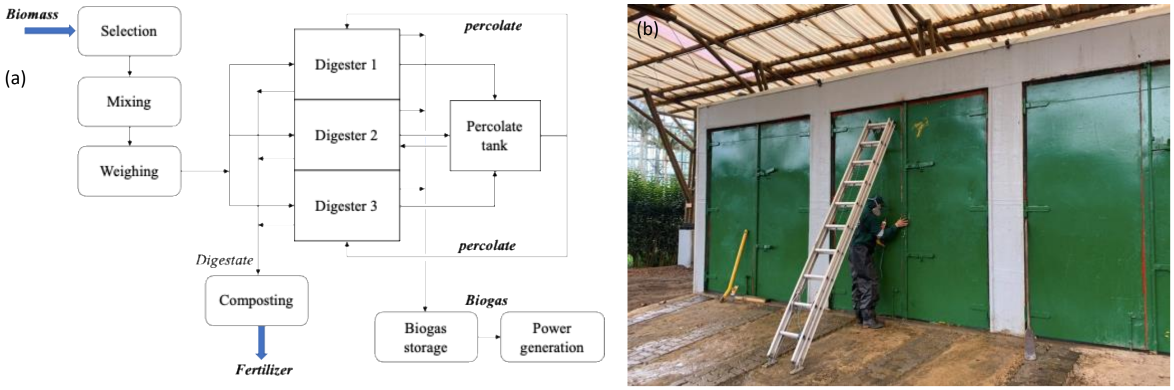

Figure 1. (a) Block diagram of the BGB dry AD plant and (b) the BGB pilot plant

Source: The authors

2.2 Experimental procedure to evaluate plant performance

Twelve tons of OFMSW were transported from Cajicá, Cundinamarca to the plant in Bogotá by the Public Services Company of Cajicá (EPC). Seven cubic meters of rumen content are transported privately from the Frigorifico BLE in Bogota. The OFMSW are screened manually to separate plastics, glass, and other non-organic materials. Both substrate and inoculum are weighed and mixed using a skid steer and then charged to the digesters. Substrates are charged to the digester using a skid steer in a 70% substrate – 30% inoculum proportion, previously defined by laboratory tests. Once the digesters are charged, the doors are closed and sealed with silicone. Biomass stabilization process lasts 7-9 days. During this process, pH and FOS/TAC parameter (volatile organic acids/buffer capacity) are monitored daily to ensure stable production. Percolate is collected in the percolate tank and recirculated to the digesters twice a day. The complete AD process last from 35 to 50 days. During the process biogas is analyzed using a portable gas analyzer Analyzer GFM 406 (GASDATA, United Kingdom). This procedure was repeated four times to determine possible failures in the process and to identify key lessons to improve the pilot plant and to guide the satisfactory design of other pilot plants.

3. RESULTS AND DISCUSSION

The initial mixture containing 70% OFMSW and 30% ruminal content presented a pH of 6.1, 20.19 % of Total Solids and 79.21% of Volatile Solids. These parameters are adequate for the dry AD process (Panigrahi & Dubey, 2019). The experimental procedure allowed to identify opportunities for the improvement of the pilot plant currently installed at BGB and formulate key lessons for the design and operation of future dry AD pilot plants. Improvements include both operational and digester structure considerations.

3.1 Performance evaluation of the BGB plant

Critical points were identified during the experimental procedure: (1) digester doors should not contain frames that can obstruct the skid steer entrance to the reactor. This will cause not only problems during the loading and discharge of the biomass, but also potential damage of the reactor doors. Hence, digesters and the loading ramps must be built at the same level. (2) Airtight doors must be specially made for the reactor; simple stainless-steel doors will not ensure proper process conditions. During the experimental procedure, oxygen entered the digester chambers through leaks located at the door frames. This caused failure of the process due to the increase of oxygen concentration inside the reactors (Figure 2a). Commercial dry digesters ensure anaerobic conditions by specially designed airtight doors. (3) Performance of the dry AD strongly depends on physicochemical parameters of the substrates: during the stabilization phase, inhibition of the process occurred due to low pH and accumulation of Volatile Fatty Acids. The OFMSW used for the present study was highly acidic. To detect inhibitions the parameter FOS/TAC was monitored (volatile organic acids/buffer capacity). According to Lossie and Pütz, a FOS/TAC above 0.5 can show inhibitions due to acidification (Lossie & Pütz, 2008). For the pilot-plant, during the stabilization phase FOS/TAC ratio was above 0.5, as a result adjustments during the process were performed. Stabilization adding sodium hydroxide to the percolate before recirculation was needed to ensure FOS/TAC ratio. Figure 2b present FOS/TAC ratio with and without stabilization.

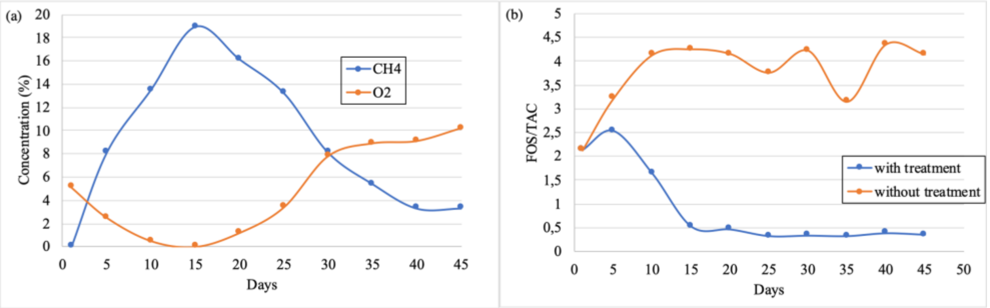

Figure 2. (a) oxygen and methane concentrations in biogas and (b) FOS/TAC monitoring during 45 of dry AD.

Finally, (4) use heat exchangers instead of electrical heating elements: temperature is an essential variable during dry AD, thermodynamic equilibrium of biological reactions, kinetics, growth rate, diversity of microorganisms, and methane generation depend on it. Electrical heating elements can suffer corrosion processes due to components present in the percolate and be destroyed or damaged. Single tube heat exchangers using hot water are more suitable for these plants. During the experiments, the electrical resistance suffered operational damages and had to be replaced or repaired several times.

4. CONCLUSIONS

AD is a technology with a growing contribution in both sustainable energy production and waste management. Dry AD is still in development around the world. This study allowed to evaluate a dry AD pilot plant in Colombia, with the aim of identifying critical points to develop lessons that can help in the design process of these facilities. Four design lessons were identified: ensuring anaerobic conditions inside the digesters using specially design airtight doors is crucial to achieve proper biogas production. Second, it is also vital to know the physicochemical characterization of the substrates. Thirdly, the use of heat exchangers instead of electrical heating elements reduces the risk of failure in keeping the adequate temperature. Lastly, digesters and the loading ramps must be built at the same level to avoid possible damages in the digester doors. The authors believe that other researchers can benefit from the experience we reported as part of the present study.

REFERENCES

APHA. (1988). *Standard Methods for the Examination of Water and Wastewater* (20th ed). American Water Works Association and Water Environment Federation.

Lossie, U., & Pütz, P. (2008). Targeted control of biogas plants with the help of FOS/TAC. *Practice Report Hach-Lange*, 4. https://tr.hach.com/asset-get.download.jsa?id=25593611361

Masebinu, S. O., Akinlabi, E. T., Muzenda, E., & Aboyade, A. O. (2019). A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. *Renewable and Sustainable Energy Reviews*, *103*(September 2018), 291–307. https://doi.org/10.1016/j.rser.2018.12.048

Mühl, D. D., & de Oliveira, L. (2022). Features of anaerobic digestion plants in the brazilian agricultural sector. *Cleaner and Circular Bioeconomy*, *1*(October 2021), 100001.

https://doi.org/10.1016/j.clcb.2021.100001

Rocamora, I., Wagland, S. T., Villa, R., Simpson, E. W., Fernández, O., & Bajón-Fernández, Y. (2020). Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresource Technology*, *299*(December 2019). https://doi.org/10.1016/j.biortech.2019.122681

Sevillano, C. A., Pesantes, A. A., Peña Carpio, E., Martínez, E. J., & Gómez, X. (2021). Anaerobic digestion for producing renewable energy-the evolution of this technology in a new uncertain scenario. *Entropy*, *23*(2), 1–23. https://doi.org/10.3390/e23020145

Velásquez Piñas, J. A., Venturini, O. J., Silva Lora, E. E., & Calle Roalcaba, O. D. (2018). Technical assessment of mono-digestion and co-digestion systems for the production of biogas from anaerobic digestion in Brazil. *Renewable Energy*, *117*, 447–458. https://doi.org/10.1016/j.renene.2017.10.085