Renewable and Sustainable Energy Reviews

Current understanding and perspectives on anaerobic digestion in developing countries: Colombia case study

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Abstract:	Anaerobic digestion (AD) technology has become increasingly important due to its contribution to sustainability and a circular bioeconomy. While AD technologies are widespread in developing countries, developed countries have mainly driven research. The aim of this research is to analyze the biogas sector development from the point of view of a developing country like Colombia. AD research ranges from laboratory mesophilic AD to psychrophilic full-scale digesters, which are intergrated with household farms as a thermal energy source for cooking, nutrient recycling for agriculture, and waste management. Research on agricultural waste substrates, inocula, and co-digestion has dominated the Colombian publications, while full-scale digesters performance research is incipient. A survey of installed digesters collected information about 996 systems and found that 79% were psychrophilic low-cost tubular digesters. Regulations for biogas were reviewed, and it was found that they are not adequate for low-cost digesters and are inherited from developed countries, ignoring the national context. Five case studies are presented on the characterization of AD technology experiences, analyzing barriers and opportunities for the technology. National networks that include farmers, NGOs, and academia are driven slowly by Colombia’s widespread AD technology, mainly on small-to medium-scale farms.
Response to Reviewers:	Dear Editor, we reviewed the manuscript attending those comments from reviers that reinforce the paper. We have changed the title, improved the abstract and introduction, and added an analysis of low cost technology AD versus "advanced digesters", also we specify literature references for the disccusion section. Now, we hope, the manuscript achive the required level thanks a lot Jaime

Febrary 3th, 2022

Aoife M. Foley
Editor-in-Chief
Renewable & Sustainable Energy Reviews

Dear Dr. Foley,

I am pleased to submit an original review entitled "Advances in anaerobic digestion technology from a developing country: A state-of-the-art review in Colombia" (word count: 9440; tables: 3; figures: 2; references: 96) by C. Tavera-Ruiz, J. Martí-Herrero, O. Mendieta, J. Jaimes-Estévez, P. Gauthier-Maradei, U. Azimov, H. Escalante and L. Castro, for consideration for publication in *Renewable & Sustainable Energy Reviews*.

This manuscript was previously submitted to your journal (RSER-D-21-01258), and was sent back to us with some coments related to the abstract, highlights, proofreading, an critical evaluation of technologies. We attend all the coments, and also updated the bibliography to include the last publications in 2021. In a sencod submittion (RSER-S-21-05983) we were called to realize an English revision of the text. We have contract the Elsevier Language editing services to check the manuscript (LE-229817-B5703BA542D8) and attend their changes.

So we back to you with this revised and updated manuscript that now follows the guide for authors, increases the focus on critical evaluation, and incorporate discussion of how lessons learned in Colombia could assist with development of sustainable energy sources in other countries. This paper presents the development of the biogas sector from a developing country point of view, finding research needs and technological developments that usually are not considered from the developed countries.

This manuscript has not been published elsewhere and is not under consideration by another journal. The paper reflects the authors' research and analysis truthfully and completely. The article properly credits the meaningful contributions of co-authors and co-researchers. We declare all authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

The authors have read and understood your journal's policies. All authors agree with submission to your esteemed journal. There are no conflicts of interest to declare.

Thank you for your consideration. We hope our manuscript is suitable for publication in your journal.

Sincerely,

Jaime Martí-Herrero
Profesor Universidad Regional Amazónica Ikiam

Manuscript Number: RSER-D-22-00720

Manuscript Title: **Advances in anaerobic digestion technology from a developing country: A state-of-the art review in Colombia**

Article Type: Review

Authors comment:

Dear reviewers, we express our acknowledgement for your revisions. The answers to your comments are presented below:

Reviewers' 1 comments:

Reviewer Comment	Author' Response
In this study, the author has reviewed various processes like research activities on AD, waste utilization for the biogas production, survey on the different digestors installed in Colombia as well as the regulation and legislation for the implementation of AD technology. Moreover, the study has been focused on the AD technologies in the Colombia region only. Also, the authors just comprehensively discussed about the different kind of waste biomass (animal manure) and digestor installed in Colombia. Even there is no discussion has been carried out based on a research perspective. The analysis of the literature papers needs to be deeper to pinpoint their argument on technological	Thanks for your comments. We have improved the discussion in the manuscript adding an analisys of low-cost tubular digester respect advanced digesters, also about biogas content reported in the Colombian literature. We have stated more clarly the aim of the research adding next paragraph in the introduction: "Although the AD technology has been applied for a long time in developing countries, and that Latin America has its proper technology development through the widespread of tubular digesters, there is a lack of analysis to understand deeper the context, the history, barriers, and opportunities from the point of view of Latin American. To fill this gap, this study aimed to understand the current status and perspectives on anaerobic digestion sector from Colombian national level, as example of Latin America developing country. We analyze AD national context, and the technologies, regulations, and lessons learned in Colombia, in order to support the widespread application of AD technology to different sectors in developing countries."

advancement and challenges. It feels more of a well-organized report on the references the author found. It is not very clear to me that what argument the author trying to make and how are the references working together to support such review argument. So, this article can be considered as a case study or survey work on the AD technologies in Colombia. Also, the authors should add their own opinion on this work	Our own opinion have been mentioned in Section 6 – Barriers, opportunities and challenges, and in Section 7 – Discussion and lessons learned.

Reviewers' 2 comments:

General comment:

Authors study an important process from the point of view of engineering applications in anaerobic digestion. Application of anaerobic digestion and survey of installed digesters is a very interesting approach. However, in some points the obtained data are not well discussed or conclusions are not sufficiently justified by the content (see specific comments included in the manuscript; the proposal of remarks are introduced using the option "Comment" in PDF document).

Reviewer Comment	Author' Response Revised Text
Authors should rewrite numerous sentences and paragraphs with the help of an expert in English language and edit the whole text.	The article was revised by Elsevier's translation service. Authors attach the certification. We have check againg the text in order to pullish the English.
Authors should change manuscript Title because the proposed title is not clear and concise.	Thanks for the comment. We changethe tittle was rewrite as: *Current understanding and perspectives on anaerobic digestion in developing countries: Colombia case study*
Abstract is not clear. Abstract must indicate the aims of the work, the main results and conclusions should be given and clearly set off from the text.	The abstract has been modified and reflects the contents mentioned in the text body with conclusions. The next sentence has been included: The aim of this research is to analyze the biogas sector development from the point of view of a developing country like Colombia.
The INTRODUCTION should include the aim of the research and a concise description of background information and related studies directly connected to the paper. The references provided are not sufficient. It is hard to recognize the aim and objectives of the paper, as well as novelty of investigations. Please rewrite the paragraph named INTRODUCTION consulting more reliable references and investigations in the field of anaerobic digestion.	The introduction was improved, and the research objective was established directly in the manuscript. Some paragraphs were included. Example**:** At the world level, the situation, challenges, and perspectives of AD have been analyzed at the continental level (for example, Europe [2–6], Africa [7–9], India [10–12], China [13,14], Latin America [15], or focus on a general concept of developing countries [16,17]. In the case of Asia and Africa can be found some publications at a national level due mainly to the national biogas programs running [8,18]. In the case of Latin America, where technology development is characterized by the widespread of psychrophilic low-cost tubular digesters in the absence of long-term national biogas programs, exists a regional analysis publication [15] **…**

	Although the AD technology has been applied for a long time in developing countries, and that Latin America has its proper technology development through the widespread of tubular digesters, there is a lack of analysis to understand deeper the context, the history, barriers, and opportunities from the point of view of Latin American. To fill this gap, this study aimed to understand the current status and perspectives on anaerobic digestion sector from Colombian national level, as example of Latin America developing country. We analyze AD national context, and the technologies, regulations, and lessons learned in Colombia, in order to support the widespread application of AD technology to different sectors in developing countries.
The discussion was not well conceived. Please provide the paragraph named Results and discussion and explain which case studies were used, which data, methods, etc.	The section 7. Discussion and lessons learned has been improved incorporating more references to the literature reviewed in the manuscript. .
Authors should conduct reliable analysis and provide more figures, diagrams, and calculations for reliable comparation and conclusions.	We have improved the quality of the graph related to bibliography, and kept the Fig 3, where can be found the organism that support biogas projects.
I found 3 figures which are not on the scientific level of such respectable Renewable and Sustainable Energy Reviews journal. It has to be improved and seriously corrected, discussed, statistically confirmed, etc.	
Why the collected data where not compared with advanced anaerobic digestion technologies? These comparations can be useful for units in Colombia.	Thanks for the comment, In the chapter 4 We have added some discussion in the manuscript around advanced technologies respect low-cost digesters, or about the Biogas quality

	Psychrophilic tubular digesters represent a simplified and successful technology in the country. Two examples of studies where this technology has been deeply analyzed in real conditions in Colombia are Castro et al. (2017) [44] and Jaime-Jaimes et al. (2021) [46]. In the first case, a 9.5m^3 total volume digester without stirring or heating devices, fed daily with cow manure and working at 23.5 ºC, produced biogas after 35 days from the start-up. The digester obtained an specific methane production (SMP) of 0.10 $Nm^3CH_4/kgSV$[44]. More information from this digester is found in section 4.3.4. When compared to mesophilic results, full scale digester fed with cow manure from [44] obtain halved SMP results (0.10 $Nm^3CH_4/kgSV$) than that reported by [87] for similar substrate at BMP tests at 36.5ºC, equal to 0.202 $Nm^3CH_4/kgSV$. This can be explained by the low HRT of the psychrophilic digester (35d) and because the digester was just beginning it operation and the AD microorganism could not be enough adapted to the psychrophilic conditions, as can be seen in the next case. The other case is a 103 m^3 operational volume digester, without mixing of active heating devices, that operates in a 17.7 ºC mean slurry temperature [46]. The digester was fed with the swine manure mixed with water to clean the stables. The influent was around 4.16 m^3/d and the HRT was 25 days. The OLR was 0.52 $kgVS/m^3_{digester}\cdot d$, the estimated SMP was 0.40 $Nm^3CH_4/kgSV$. The the key aspect of this digester was that has been operating for more than eight years. More information from this digester is found in section 4.3.5. Microbiological analysis revealed that the microbiota was adapted to psychrophilic conditions, thereby increasing methanogenic archaea content while decreasing bacterial populations. In this case, mesophilic results from [87] for swine manure BMP test at 36.5ºC reports 0.322 $Nm^3CH_4/kgVS$, do not show better results respect an

	eight years old psychrophilic digester. Although the HRT is reduced for psychrophilic conditions (25d), the 8 years old adapted microorganism looks to be able to produce similar or greater amounts of biogas than mesophilic. From a technological point if view, there are room for action to improve those results, for example adding a previous process of pretreatment. An effective pretreatment can facilitate the degradability of complex organic molecules to convert them into smaller compounds to be used as substrates in conventional AD [88]. Thermal pretreatment of manure fibers with NaoH [89], or alkaline microwaving pretreatment [90] demonstrate that biogas production is increased. But adding most sophistication to the system, increase the investment, maintenance and operational cost of the digester, making it less accessible ti medium and small farmers. Also, heating or energy conservation are important for improving the suitability of AD in cold regions [91]. When biogas is not used to generate electricity, so no waste heat is able from a Combined Heat and Power System (CHP), the biogas could be used to heat the digester. But, in Norway (temperature ranges from 1 to 13 °C) a burner was installed to heat the substrates to 37°C, being necessary to consume 85 kWh of the 105 kWh of the total energy produced by biogas [92]. So, if there are no waste heat from a CHP, the heating of the digesters, without increasing its complexity and investment cost, can be using passive solar heating design [26,28, 93]. Finally, low-cost tubular digester sacrificed more efficiency by more technological accessibility to farmers, balancing the lack of sophistication, with higher reactor volumes and passive devices for heating and mixing.

Authors should discuss more detailed the properties of biogas produced by different technologies. From the point of view of industrial application, it is very important.	Thanks, we have added new paragraph in the chapter 4, where the biogas properties are now discussed. . Regarding the quality of biogas, in terms of methane content, it could be inferred from previous studies on tubular household digesters using different substrates, that it remains above 40% and achieves an increase with temperature from psychrophilic conditions (40–65%) to mesophilic (60–70%). This makes it possible to cover the fuel needs for thermal energy, cooking and heating, mainly, and in some cases to supply mechanical energy in engines of agricultural machines. Small-scale biodigesters (8-15 m3) produce around 3 m3/day, and allow to meet the energy requirements in cooking food for 5-8 people. Medium-scale biodigesters (>40 m3) produce approximately 8 m3/day, and biogas is used for sterilization of milking machines and heating of piglets. Besides, in the case of some small-scale biodigesters, H_2S is removed through a packed iron oxide biogas filter. However, on a medium scale there is an obstacle to using biogas in other more specialized applications for which advanced desulfurization technologies or low-cost natural materials are required in the purification and upgrading of biogas. Due to the fact that the technology has come out of the laboratory directly to rural areas, several risks have been identified, among them: CO_2 emissions, CH_4 and NH_3 explosion, high concentrations of H_2S cause negative effects on the water, it is very toxic irritant and can inhibit respiration. However, all these risks are currently not considered.
I have carefully checked the manuscript list of references and I found only 5 manuscripts from Renewable and Sustainable Energy Reviews. This may give an impression to readers that the work is outside the scope of Renewable and Sustainable Energy Reviews journal, although journal publish routinely in this area. I ask that authors rework the list of references.	A bibliographic review of publications in the journal Renewable and Sustainable Energy Reviews related to the subject was carried out. 13 additional publications were added along the manuscript for a total of 18 references to this journal • O'Connor S, Ehimen E, Pillai SC, Black A, Tormey D, Bartlett J. Biogas production from small-scale anaerobic digestion plants on European farms. Renew Sustain Energy Rev 2021;139:110580. https://doi.org/10.1016/j.rser.2020.110580. • Edwards J, Othman M, Burn S. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renew Sustain Energy Rev 2015;52:815–28. https://doi.org/10.1016/j.rser.2015.07.112. • Lora Grando R, de Souza Antune AM, da Fonseca FV, Sánchez A, Barrena R, Font X. Technology overview of biogas production in anaerobic digestion plants: A European evaluation of

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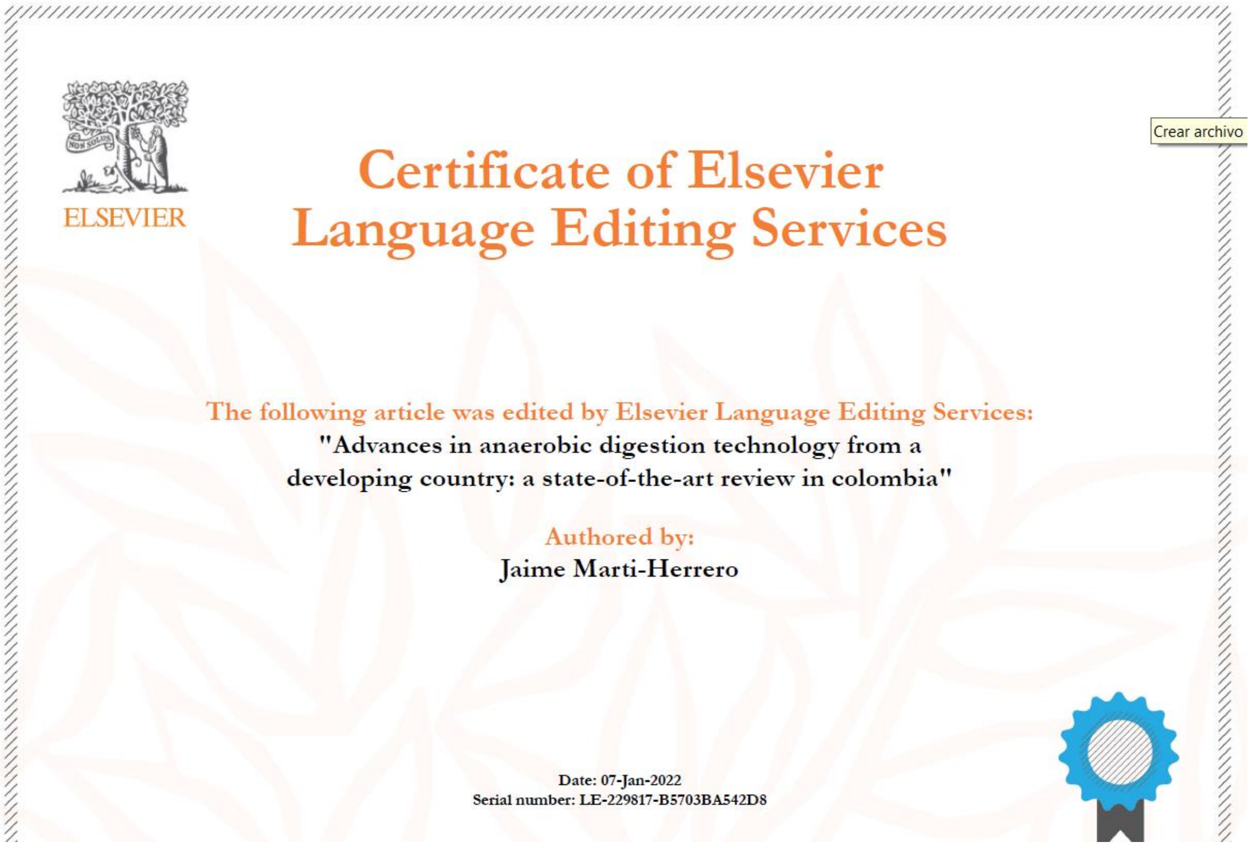
	• Yao Y, Huang G, An C, Chen X, Zhang P, Xin X, et al. Anaerobic digestion of livestock manure in cold regions: Technological advancements and global impacts. Renew Sustain Energy Rev 2020;119:109494. https://doi.org/10.1016/j.rser.2019.109494. • Gunes B, Stokes J, Davis P, Connolly C, Lawler J. Pre-treatments to enhance biogas yield and quality from anaerobic digestion of whiskey distillery and brewery wastes: A review. Renew Sustain Energy Rev 2019;113:109281. https://doi.org/10.1016/j.rser.2019.109281. • Becker CM, Marder M, Junges E, Konrad O. Technologies for biogas desulfurization - An overview of recent studies. Renew Sustain Energy Rev 2022;159:112205. https://doi.org/https://doi.org/10.1016/j.rser.2022.112205. • Mulu E, M'Arimi MM, Ramkat RC. A review of recent developments in application of low cost natural materials in purification and upgrade of biogas. Renew Sustain Energy Rev 2021;145. https://doi.org/10.1016/j.rser.2021.111081. • Stolecka K, Rusin A. Potential hazards posed by biogas plants. Renew Sustain Energy Rev 2021;135:110225. https://doi.org/10.1016/j.rser.2020.110225. • Mutungwazi A, Mukumba P, Makaka G. Biogas digester types installed in South Africa: A review. Renew Sustain Energy Rev 2018;81:172–80. https://doi.org/10.1016/j.rser.2017.07.051.
Comments into the document:	
L8. Abstract is not clear. Abstract must indicate the aims of the work, the main results and conclusions should be given and clearly set off from the text.	The abstract has been modified and reflects the contents mentioned in the text body with conclusions. Also, the sentence "The aim of this research is to analyze the biogas sector development from the point of view of a developing country like Colombia" has been included
P1-L42. Higlights should be concise. These are too general.	The highlights were modified in order to be more accurate. • Half of the Colombian AD publications are from the last three years. • 79% of the digesters are low-cost and run under psychrophilic conditions. • Mesophilic AD research on substrates, co-digestion, and inoculum dominates.

	• There is a lack of regulation, support, and psychrophilic AD research. • Multidisciplinary networks drive the spread and research of low-cost digesters.
P12-L47. Why is this discussed? The number of publication is not reliable parameter for these analysis. In my opinion, sometimes one good article gives more useful informations than 100 publication.	. We agree that some articles are more useful than many others, but we think that the dynamic of number of papers published is an interesting parameter that shows the evolution of the interest of the topic. It is not about quality of papers, is about the interest in the topic.
P27-L39. Missing type	thanks**,** it was corrected.
P46-L5. Conclusion is not concise. The main results should be given.	thanks for the comment. We rewrote and improve conclusions section The main objective of this review was analyzing the current state of anaerobic technology, barriers, and opportunities in developing countries such as Colombia. Research and development on AD have been evolving in recent years, highlighting the interest of academia and industrial sector and increasing the implementation of this technology. Although AD technology has been in use since many years, there are still significant gaps in knowledge about its implementation and performance under long term psychrophilic conditions in rural areas, where the technology was initially developed through trial and error. Research has focused on studying AD performance, using diverse substrates and local inoculum at the laboratory level to promote the sustainability of different agricultural sectors. The review carried out in this study found that manure from various livestock farms (mainly cow, horse, pig, buffalo, goat, and fish manure) is the most important substrate used in Colombia (69%), followed by organic wastes from other unspecified sources (31%). The main characteristics of the inoculum are its origin, VS content, and SMA. The main sources of inoculum used are stabilized cow manure and pigs.

	Reports published by the Colombian Environment Ministry indicate that currently, there are approximately 5,700 digesters installed in the country. The departments with the highest number of digesters are Caldas, Cundinamarca, and Santander. The most commonly used type of digester in Colombia is the low-cost tubular configuration (79%). The remaining 21% correspond to other models (batch and lagoon) and are not specified. Even though anaerobic digestion is considered a promising technology in Colombia, the AD sector faces critical challenges, such as feedstock pre-treatment using low-cost technologies, developing a sustainable market for biogas and digestate, and process safety in small and medium digesters. As well, the development of policies for renewable energy sources has been identified, and it is necessary to structure policies focused on AD to implement the technology throughout the country. Finally, academic research is approaching the study of full-scale psychrophilic digesters, the vast majority of installed digesters in Colombia, as in the rest of developing countries.

Previous version of the manuscript was revised by English language editing service



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"Advances in anaerobic digestion technology from a developing country: a state-of-the-art review in colombia"

Authored by:

Jaime Marti-Herrero

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Current understanding and perspectives on anaerobic digestion in developing countries: Colombia case study

C. Tavera-Ruiz [1,2], J. Martí-Herrero [3,4*], O. Mendieta [1,5], J. Jaimes-Estévez [1], P. Gauthier-Maradei [1], U. Azimov [6], H. Escalante [1], L. Castro [1]

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Abstract

Anaerobic digestion (AD) technology has become increasingly important due to its contribution to sustainability and a circular bioeconomy. While AD technologies are widespread in developing countries, developed countries have mainly driven research. The aim of this research is to analyze the biogas sector development from the point of view of a developing country like Colombia. AD research ranges from laboratory mesophilic AD to psychrophilic full-scale digesters, which are intergrated with household farms as a thermal energy source for cooking, nutrient recycling for agriculture, and waste management. Research on agricultural waste substrates, inocula, and co-digestion has dominated the Colombian publications, while full-scale digesters performance research is incipient. A survey of installed digesters collected information about 996 systems and found that 79% were psychrophilic low-cost tubular digesters. Regulations for biogas were reviewed, and it was found that they are not adequate for low-cost digesters and are inherited from developed countries, ignoring the national context. Five case studies are presented on the characterization of AD technology experiences, analyzing barriers and opportunities for the technology. National networks that include farmers, NGOs, and academia are driven slowly by Colombia's widespread AD technology, mainly on small-to medium-scale farms.

Highlights:

- Half of the Colombian AD publications are from the last three years.
- 79% of the digesters are low-cost and run under psychrophilic conditions.
- Mesophilic AD research on substrates, co-digestion, and inoculum dominates.
- There is a lack of regulation, support, and psychrophilic AD research.
- Multidisciplinary networks drive the spread and research of low-cost digesters.

Keywords

Biogas; developing country; renewable energy; household digester; policies; psychrophilic anaerobic digestion

Word count: 9440

List of abbreviations

AcoD: Anaerobic Co-Digestion

ADB: Asian Development Bank

AD: Anaerobic Digestion

AfDB: African Development Bank

ANLA: Autoridad Nacional de Licencias Ambientales (National Environmental Licensing Authority)

ASPROINCA: Association of Indigenous and farmers of Riosucio

BBIW: Bottled Beverage Industry Waste

BDI: International Development Bank

BM: Bovine Manure

BMP: Biochemical Methane Potential

CfM: Coffee Mucilage

CHP: Combined Heat and Power system

CIPAV: Centre for Research on Sustainable Agricultural Production Systems

CIR: Cocoa industry residues

CkM: Chicken manure

CREG: Comisión de Regulación de Energía y Gas (Energy and Gas Regulation Commission).

CW: Cheese Whey

DWS: Domestic Wastewater Sludge

EBRD: European Bank for Reconstruction and Development

EIB: European Investment Bank

EROEI: Energy Return on Energy Invested

FAER: Fondo de Apoyo Financiero para la Energización de las Zonas Rurales Interconectadas (In English: Financial Support Fund for Energization of the Interconnected Rural Zones).

FANZI: Fondo de apoyo financiero para la energización de las zonas no interconectadas (In English: Financial support fund for Energizing non-interconnected Zones)

FAO: World Bank, Food and Agriculture Organization of the United Nations

FECF: Fondo Especial Cuota de Fomento (In English: Special Fund for Development Fee)

FENOGE: Fondo de Energías No Convencionales y Gestión Eficiente de la Energía (Non-Conventional Energies and Efficient Energy Management Fund).

FFJC: Fondo Nacional de Financiamiento de la Ciencia, Tecnología e Innovación Francisco José de Caldas (In English: National Fund for the Financing of Science, Technology and Innovation Francisco José de Caldas).

FINAGRO: Fund for the Financing of the Agricultural Sector

FINDETER: Financiera de Desarrollo Territorial S.A. (In English: Territorial Development Finance).

FMAM: Fondo para el Medio Ambiente Mundial (In English: Fund for the Global Environment)

FMI: Fondo Monetario Internacional (In English: International Monetary Fund).

FNR: Fondo Nacional de Regalías (In English: National Royalty Fund)

FSSRI: Fondo De Solidaridad Para Subsidios y Redistribución de Ingreso (In English: Solidarity Fund for Subsidies and Income Redistribution).

FW: Food Waste

GEERED: Global Energy Efficiency and Renewable Energy Fund

GEF: Global Environment Facility

GIZ: German Society for International Cooperation

h: Hour

HM: Horse manure

IAF: Inter-American Foundation

IAPP: Industry-academia partnerships

IDB: Inter-American Development Bank

IFAD: International Fund for Agricultural Development

IFC: International Finance Corporation

IPSE: Planning and Promoting Energy Solutions in Non-Interconnected Zones.

JICA: Japan International Cooperation Agency

kg: Kilograms

KIW: German bank Kreditanstalt für Wiederaufbau

kW: Kilo Watts

LCA: Life Cycle Assessment

MARD: Ministry of Agriculture and Rural Development

MBW: Municipal biowastes

MESD: Ministry of Environment and Sustainable Development.

MME: Ministry of Mines and Energy

Mt: Megatons

NAMAS: Nationally Appropriate Mitigation Action

NCS: Non-centrifugal cane sugar

Nm^3: Normal cubic meters

OWW: Offal wastewater

PM: Pig Manure

PS: Primary sludge

PVC: Polyvinylchloride

PWS: Pig Waste Sludge

PWW: Paunch wastewater

RedBioCol: Red Colombiana de Energía de la Biomasa (In English: Colombian Biomass Energy Network).

RL: Ruminal Liquid

SCM: Sugarcane Molasses

SCS: Sugarcane Scum

SENA: Servicio Nacional de Aprendizaje (In English: National Learning Service)

SWW: Slaughter wastewater

SMA: Specific Methanogenic Activity

TJ: TeraJoules

UASB: Upflow Anaerobic Sludge Blanket

UNAL: Universidad Nacional de Colombia (In English: National University of Colombia)

UNDP: United Nations Development Program.

UNEP: United Nations Environment Program

UNIDO: United Nations Industrial Development Organization

UPME: Mining and Energy Planning Unit

USAID: United States Agency for International Development

VFA: Volatile fatty acids

VN: Vinasse

VS: Volatile Solids

ZNI: Non-Interconnected Zones

1. Introduction

Anaerobic digestion (AD) is a useful technology for waste management. This technology uses a substrate, which typically comprises animal manure, wastewater, or organic waste, transforming it into biogas and digested. Biogas is recovered as energy via cogeneration and used for cooking, electrical energy generation, or heating, while the digestate is used as a fertilizer. Due to the relevance of AD as a key technology for waste valorization, interest in its research and development has been gradually growing worldwide, thus allowing an improvement in the conditions and equipment required for AD, favouring its implementation [1].

At the world level, the situation, challenges, and perspectives of AD have been analyzed at the continental level (for example, Europe [2–6], Africa [7–9], India [10–12], China [13,14], Latin America [15], or focus on a general concept of developing countries [16,17]. In the case of Asia and Africa can be found some publications at a national level due mainly to the national biogas programs running [8,18]. In the case of Latin America, where technology development is characterized by the widespread of psychrophilic low-cost tubular digesters in the absence of long-term national biogas programs, exists a regional analysis publication [15].

In developing countries, AD technology has become crucial not only for waste valorization but also to meet the energy demand, especially remote, non-interconnected rural areas, thus enabling developing countries to supply cheap energy, and to improve the quality of life of rural inhabitants.

The implementation of AD in developing countries is primarily focuses on small-scale biodigesters, commonly known as household biodigesters. This type of installation has the advantages of a low volume (maximum 10 m^3) and size, low cost, easy handling, and maintenance. In developing countries, pig or cow manure is commonly used as a substrate, and the biogas is mainly used for cooking and electricity generation [19].

Colombia is a developing country in South America, where around 66% of the national territory does not have public electricity services through the National Interconnected System

[20]. The main sources of residual biomass are agricultural activities [21], livestock production, and the processing agro-industry. This residual biomass can support up to 15% to 28% of the end-use energy mix in the country [22]. In Colombia, AD has been adopted for the sustainable management and energy recovery of organic wastes and it is considered a clean and environment-friendly technology that can help rural communities meet their energy needs and, consequently, improve their living conditions [23]. Fixed domes, floating drums, and tubular digesters are the most common models implemented in developing countries [24]. Tubular digesters (or plug-flow reactors) are popular in Colombia owing to their low cost, the possibility of operation at various temperatures, and ease of implementation and handling [25,26]. Besides, these digesters do not require mixing to avoid material sedimentation inside the reactor or active heating to increase the temperature of the liquid. Passive solar heating designs have been used to adapt the tubular model to cold climate regions [27,28]. These observations indicate that AD technology is an opportunity to promote sustainable agriculture and improve living standards in rural areas.

Although the AD technology has been applied for a long time in developing countries, and that Latin America has its proper technology development through the widespread of tubular digesters, there is a lack of analisys to understand deeper the context, the history, barriers, and opportunities from the point of view of Latin American. To fill this gap, this study aimed to understand the current status and perspectives on anaerobic digestion sector from Colombian national level, as example of Latin America developing country. We analyze AD national context, and the technologies, regulations, and lessons learned in Colombia, in order to support the widespread application of AD technology to different sectors in developing countries.

The review is structured as follows: First, research on AD facts has been discussed. Second, under controlled conditions, wastes used as substrates for biogas production at the laboratory level were analyzed. Third, AD technology development in the household sector, including a nationwide analysis of the digesters by administrative regions (departments in Colombia), has been reviewed. Fourth, a review of Colombia’s regulatory entities and current legislation on renewable energy sources, including AD, is presented. Finally, barriers, lessons learned, challenges, and opportunities have been discussed to develop technology focusing on local farmers/rural populations.

2. AD facts in Colombia

The 1970s and the first half of the 1980s witnessed a rapid growth in the use of biogas, mainly in Asian, Latin American, and African countries [29]. Different enterprises —*government and non-governmental organizations*— promoted this growth that facilitated the installation, development, and technology diffusion, mostly in rural areas. Globally, China and India were the two largest household biogas users owing to their experience in technology and economic and technical support through public investment [15]. However, in Latin America, long-term financial subsidies were absent, and there was a lack of institutional support and follow-up. Therefore, the number of digesters installed in this region was considerably low [30,31]. Even though most installed digesters are found in Asia, remarkable research achievements have been reported from Latin America, contributing to increasing operational, technical, social, and environmental experiences [15,32].

In Colombia, the first design and installation manual for tubular digesters was published in 1987 [33]. Introduced, this model became the most widespread in Latin America. Since then, the Center for Research on Sustainable Agricultural Production Systems (CIPAV in its Spanish initials) has worked with farmers on AD research projects (largely with the tubular digester model) related to sustainable livestock, ecological restoration, and environmental services. The CIPAV edits and publishes the international peer-reviewed electronically and indexed journal Livestock Research for Rural Development (LRRD), an international peer-reviewed and indexed journal [34] to foster knowledge-sharing on topics covering sustainable rural development with a focus on AD [35].

Since the early 2000s, the Fundación Para la Producción Agropecuaria Tropical Sostenible, linked to The University of Tropical Agriculture Foundation, has played a pivotal role in AD promotion, installation, and research, with a focus on small and medium farmers, in Colombia. The foundation has been working on implementing digesters for more than 20 years, sharing experiences from Vietnam and Cambodia in South Asia, where it has worked on research, training, and rural development [36].

Considering household digesters as an alternative to promote the reduction of watershed pollution from livestock and agricultural exploitation, during the fourth conference on "Network of Biodigesters for Latin America and the Caribbean" (RedBiolac), it was proposed to engage in partnerships with the experiences of a Colombian Network [37]. As a result, in 2012, the Colombian Biomass Energy Network (RedBioCol) was founded. Currently, RedBioCol integrates experiences with different types of digesters at different scales, based on experiences from industry, small users, and academies. RedBioCol also focuses on strengthening AD technology by solving pollution-related problems, transforming waste into energy products, and promoting technology adoption by farmers [38].

Initially, AD technology in Colombia was implemented specifically for wastewater treatment. However, with the arrival of RedBioCol and its efforts to promote this technology, its use was expanded as an alternative for treating rural waste. In the last ten years, considering the advantages of AD, Colombian researchers have shown an interest in studying operating conditions and influencing variables that could allow the optimisation of this process.

Regarding the research on AD, scientific publications on biogas in Colombia have grown rapidly in the last decade. A systematic review of the existing publications on AD in Latin America and Colombia was conducted using the keyword search method in the Scopus database (keywords: co-digestion, anaerobic digestion, biogas, rural Figure 1-a shows). The Latin American countries with the largest number of publications from 1992 (the oldest publication) to 2022 are Brazil with a total of 3620 publications, followed by Mexico (1659), Chile (606), and Colombia with a total of 573 publications. Brazil has been the leader in anaerobic digestion in Latin America since the 19th century; the country has had a special interest in research and investment in alternative energy sources, including bioethanol and biodiesel. This interest has resulted in crucial participation of the federal government in terms of regulation, incentive programs for alternative energy sources, and market interventions, which favored the research and development of renewable technologies such as digestion.

Likewise, in Brazil, there is a high ability for private investment and entrepreneurship to support these types of projects, and a high experience in experimentation with biogas technologies that dates back from 1970 [39,40].

Figure 1-b shows the publications on AD per year by Colombian institutions or entities, with a total of 573 papers published to date. The first publication appeared in 1992, which presented the effects of mass transfer on the half-saturation constant for H_2 uptake kinetics [41]. However, between 1993 and 1997, there was a lacuna in research. Since 1997, there was an average of one publication per year until 2006, when the number of publications increased year by year, eventually reaching 82 in 2021. This growing trend is due firstly to the great potential of this technology that arouses a lot of interest in Colombian researchers, and secondly, to the initiative for the implementation and development of the technology that RedBioCol has driven. While reviewing Colombian research, it was noted that many of these were carried out in collaboration with universities or research centers in developed countries such as the United States, UK, France, Germany, and Spain.

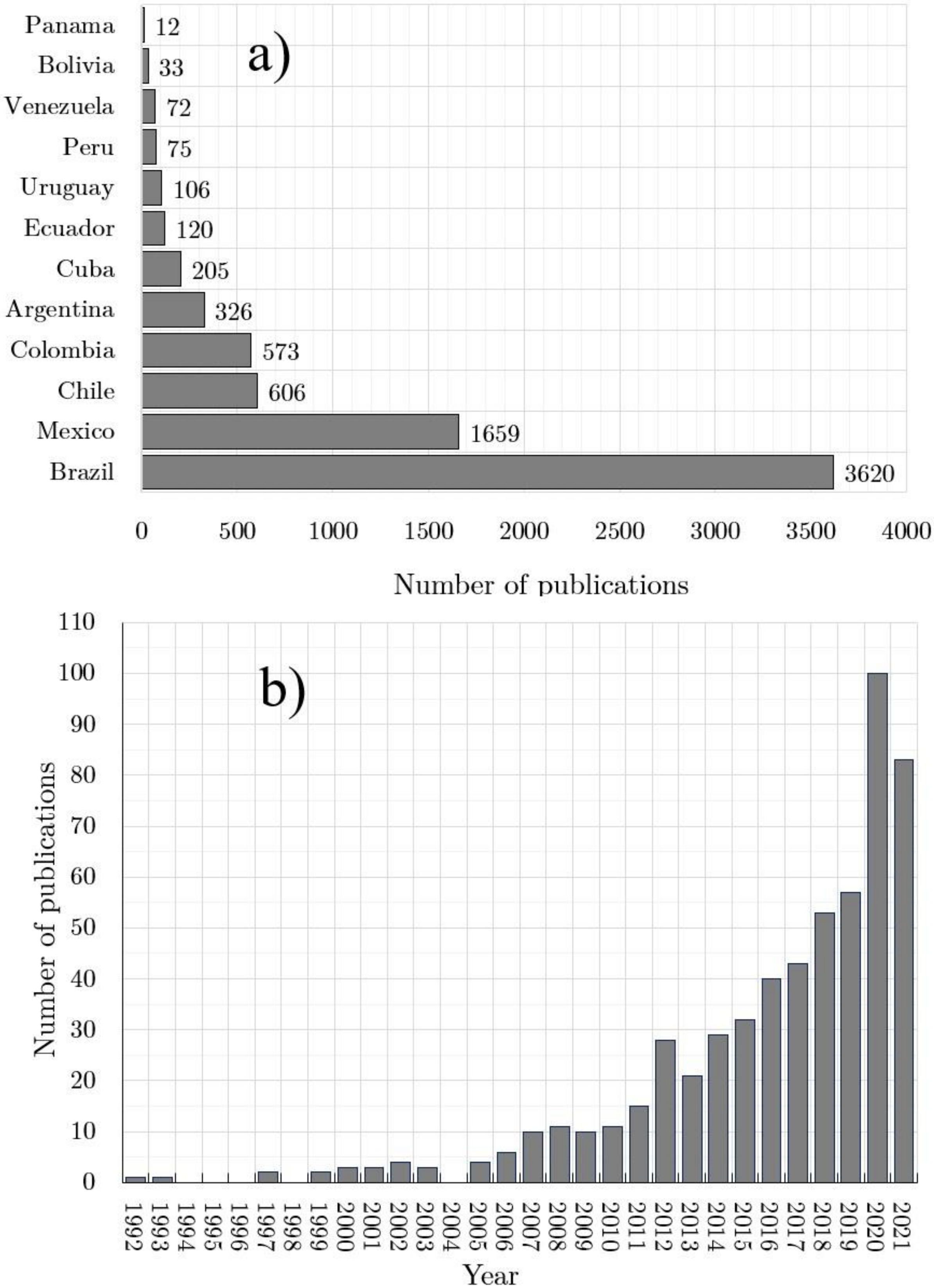
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Figure 1. Publications on AD from 1992 to 2021: a) Latin-American countries and b) Colombian publications by year.

The investigations on AD carried out in Colombia focused on studying the process using different feedstock (substrates and inoculums) from local agricultural and agro-industrial activities, configurations of digesters, and operating conditions. It is noteworthy that hundreds of low-cost digesters were already working on the farms [42], and the academia learned full-scale AD processes from the farmers, initiating a feedback process. This two-way knowledge transfer was carried out with the help of small and medium farmers, developing different methods, according to the biomass available in each area, in order to value them and offer a renewable energy alternative.

Additionally, other Colombian researchers have focused on full-scale household digesters to determine the parameters and performance of the process under real conditions [43–48]. Monitoring comprised taking frequent samples (influent, effluent, digestate, and biogas). These samples were characterized by measuring the biochemical methane potential (BMP), methane content, residual methane potential, specific methanogenic activity (SMA), organic matter content and consumption, volatile fatty acids, biogas production, methane concentration, and pH. These data were used to calculate energetic and economic potential with the implementation of the technology. Furthermore, the researchers proposed improvements to the process that increased the yield and quality of the biogas obtained and stabilized the effluent for agricultural reuse, thereby allowing a constant development of the technology on a small scale.

3. AD potential from Colombian waste

In the Colombian agricultural context, many residual biomass sources can be used as substrates. On average, Colombian organic waste production is approximately 117.5 Mt/year. From a global point of view, using these residues as an energy source can potentially produce 449,801.85 TJ/year [21].

Among the substrates studied, a wide variety of raw materials predominated and can be classified into three large groups: agricultural residues (benefit wastes and fruit wastes), domestic and industrial residues (food waste, cheese whey, or slaughterhouse wastewater), and livestock residues (pig, cattle, horse, and poultry), with their BMP ranging between 0.03 Nm^3 CH_4/kg VS and 0.78 Nm^3 CH_4/kg VS, which represents an energy contribution between 0.3 kWh/kg VS and 7.77 kWh/kg VS [49,50].

Table 1 displays a compilation of the experimental BMP data published in the literature. The search criteria were as follows: i) biomass (inoculum and substrate) from Colombia, ii) experimental conditions (inoculum/substrate ratio and mesophilic temperature range) [51], and iii) articles published since 2010. Before 2010, no BMP tests were reported in Colombia. We consulted the following databases: Scopus, Web of Science, Redalyc, and Science Direct. In addition, the information published in RedBioLac and Livestock Research for Rural Development journals was also considered. Based on these criteria, 29 papers were identified. Most experimental data were published from 2018 to 2022, indicating a keen interest in this research topic.

Studies have shown that the anaerobic co-digestion (AcoD) of mixtures with different substrates resulted in improved process performance, given a better balance in the composition of the mix that stimulates biogas and methane production [52]. Additionally, AcoD can improve internal conditions, such as pH or volatile fatty acid (VFA) content, representing a stable process without inhibition risks. The experimental data presented in Table 1 reveal an increase in mass yield, between 14% and 22%, in systems where the main substrate in AcoD consisted of sugarcane scum with agricultural crop residues [53] and chicken manure mixed with industrial wastes [54].

The Colombian studies revealed a variety of potential waste-as-resources used both as substrate and inoculum (after substrate stabilization) in AD or AcoD processes. The studies on these widely available biomass resources highlight the increasing interest in AD in Colombia and their potential energy, economic, and environmental impacts, which can be realized through bioprocesses.

AD comprises hydrolysis, acidogenesis, acetogenesis, and methanogenesis, carried out by a microbial consortium. The inoculum is an important factor in conducting a BMP test to determine the biogas potential of a substrate. A suitable inoculum can increase the degradation rate, enhance biogas production, shorten the starting time, and make the digestion process more stable [55]. Selecting an inoculum involves considering the origin, volatile solid content, and specific methanogenic activity. The literature reports two sources of microbial consortia (inoculum) for BMP assays: granular/floccular (9 papers) and different manures (16 articles). Owing to their high availability and promotion of their use by various entities such as RedBiolac and National Learning Service (SENA, by its initials in Spanish), manures generated in livestock activities are widely used as a source of inoculum.

Table 1. Summary of BMP of different sources of substrate and inoculum in Colombia.

Year	Reference	Substrate (s)	Inoculum	BMP* (Nm^3CH_4 /kg VS) Mono-digestion	BMP* (Nm^3CH_4 /kg VS) Co-digestion
2012	[56]	Fique bagasse	Ruminal liquid (RL) and pig waste sludge (PWS)	0.30	-
2014	[57]	Fique bagasse	Ruminal fluid (RF) and pig manure sludge (PMS) (Mixture 1:1)	0.35	-
2015	[58]	Chicken manure (CkM)	Cattle slurry	0.55	-
2016	[59]	Vinasse (VN) and CkM	Cattle slurry	-	0.65 (VN:CkM 3:1) 0.56 (VN:CkM 1:3)
2016a	[60]	Municipal biowaste from a university restaurant	From UASB reactors and an anaerobic sludge digester	0.07	-
2016b	[61]	Municipal biowastes (MBW) and selective collection with domestic wastewater sludge (DWS)	Obtained from an anaerobic digester of the municipal WWTP of DWS	0.104 (MBW) 0.073 (DWS)	0.106 (DWS:MBW 1:4)
2016	[62]	Sewage sludge primary sludge(PS) and food waste (FW)	Digested sludge	0.19 (PS) 0.20 (FW)	0.25 (PS:FW 1:2.3)
2016	[63]	Slaughterhouse wastewater	Cattle manure	0.73	-
2017	[64]	Pig manure (PM), municipal solid waste (MSW), and Cocoa industry residues (CIR)	Sludge from a biodigester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca.	0.44 (PM) ** 0.38 (MSW) ** 0.20 (CIR) **	
2018	[65]	Cheese whey	Cattle slurry	0.51 - 0.60	-
2018	[54]	Chicken manure (CkM), sugarcane molasses (SCM), and cheese whey (CW)	Cattle manure	0.34 (CkM)	0.57–0.66 (CkM:SCM:CW 1:1:1)
2018	[66]	Fruit waste: banana, dragon fruit, mango, goldenberry, and pineapple	Pig manure (PM)	0.35 (dragon fruit) ** 0.26 (mango) ** 0.24 (goldenberry) **	-

				0.23 (banana) ** 0.22 (pineapple) **	
2018	[67]	CIR, PM, organic fraction of municipal solid waste (MSW), and bottled beverage industry waste (BBIW)	Sludge from a digester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca.	0.48 (PM) ** 0.33 (MSW) ** 0.25 (CIR) ** 0.13 (BBIW) **	0.12–0.36 (mixing ratio not reported)
2018	[50]	CIR, PM, and coffee mucilage (CfM)	Sludge from a biodigester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca	0.45 (CfM) ** 0.78 (CIR) ** 0.53 (PM) **	-
2018	[68]	Food waste from the restaurant of the University of Valle	Sludge from a methanogenic reactor that treats cattle slaughter wastewater	0.15	-
2019	[69]	Bovine manure (BM), horse manure (HM), and PM	Diluted manures (BM, HM, and PM) were used as a source of inoculum	0.104 (BM) 0.170 (HM) 0.145 (PM)	0.19 (BM:PM 3.4:1) 0.47 (BM:HM 1:1.8) 0.42 (BM:HM:PM 6.5:1.5:1)
2019	[70]	Mango fruit waste	PM	0.75 **	-
2019	[71]	Fish waste	Anaerobic sludge from a UASB reactor treating wastewater from a slaughterhouse	0.47 (1% TS)	-
2019	[49]	Aged landfill waste	A mesophilic anaerobic digester treating municipal wastewater solids	0.035–0.038	-
2019	[72]	Wastewater (WW) from the Pontificia Bolivariana University and aerobic sludge from secondary treatment (AS)	Anaerobic sludge from a wastewater treatment plant of soft drinks	-	0.32 (WW:AS 1:60)
2019	[43]	Cattle manure	Cattle manure	0.69	-
2019	[71]	Grass from public green spaces of the tropical city of Palmira, Colombia	Mesophilic anaerobic sludge from a UASB reactor treating domestic wastewater from Ginebra, Colombia	0.33	-

2020	[73]	Gulupa (purple passion Fruit)	PM	0.41 (Gulupa peel) ** 0.31 (Gulupa pectin free) **	-
2020a	[74]	Sugarcane scum (SCS)	Cow manure digested sludge	0.23 (12.5% SCS Dilution)	-
2020b	[53]	Sugarcane scum (SCS) and agricultural crop residues (ACR) from the non-centrifugal cane sugar agribusiness sector	Cow manure digested sludge	0.21 (SCS) 0.26 (ACR)	0.28 (ACR:SCS 3:1)
2020	[75]	Municipal solid waste from a regional landfill in Valle del Cauca, Colombia	Granular sludge from an anaerobic digester receiving wastewater from a cattle and pig slaughterhouse in Valle del Cauca, Colombia	0.43	-
2021	[76]	Mixture of food waste (FW) / garden waste (GW)	Mixture of granular sludge:flocculant sludge	0.07 (FW) 0.08 (GW)	0.26 (FW:GW 1.7:1)
2021	[77]	Food waste (FW)	Mixture of granular sludge:flocculant sludge 75:25 v/v	0.09 (fresh) 0.135 (thermally pretreated)	-
2021	[78]	Slaughter wastewater (SWW), offal wastewater (OWW), and paunch wastewater (PWW) from a Colombian bovine slaughterhouse	Mesophilic cattle sludge	0.505 (SWW) 0.425 (OWW) 0.154 (PWW)	0.51 (SWW:OWW 2:1)

* BMP values were normalised to standard conditions (273.15 K and 100 kPa). Co-digestion ratio in VS.

** Does not report temperature and pressure conditions.

The main inoculum used in BMP tests is stabilized manure from cows (seven research studies) and pigs (three research studies) that serves as alkalinity or nitrogen source. The volatile solid content of the inoculum is a crucial factor because this variable is related to the content of active microbial biomass and determines whether dilution is required. Several papers have reported the contents of volatile solids ranging from 15 to 84.5 g SV/kg and 7.9 to 80.5 g/kg for granular/floccular and manure inoculums, respectively. SMA is a critical factor in AD that determines the methane-producing capability of the inoculum for a specific substrate at the concentration level, wherein substrate availability is not a limiting factor [79]. Unfortunately, this information was absent in most of the reviewed articles (69%). In the articles containing this information, the SMA reported ranged between 0.14–0.17 g COD/g VS for flocculent/granular and between 0.023–0.152 g COD/g VS for manure.

4. Development of AD technology

AD is carried out in biogas digester systems. These systems can be categorized into small-to medium-sized (5-20 m^3), and large-scale (>20 m^3) plants. The medium (a term not widely applied) and large-scale refer, generally, to plants implemented in industrialized zones with large amounts of substrate production (such as wastewater sludge from wastewater treatment plants or agricultural or industrial plants). In contrast the small-scale refers to domestic, household decentralized, farm, and communal biogas plants [80].

4.1 AD technology development at small and medium scale

The term household digester is extensively used to refer to small-scale biogas plants with low technological requirements, which are generally used in rural areas. AD application in household digesters offers numerous benefits, such as easy installation and operation, low cost, and size flexibility. The most well-known digester designs are fixed domes, floating drums, covered lagoons, and tubular digesters, which are considered the original Colombian technology.

In particular, at the end of the 1980s, the CIPAV introduced the tubular digester, also called the Taiwan type, in Colombia [81]. Small users have used this design as one of the main configurations for carrying out the AD process in rural areas [82]. This type of digester is generally cylindrical and is made of polyvinyl chloride, polyethylene (the same plastic used for greenhouses), or geomembrane. The digesters are semi-buried in a trench, leaving the biogas bell visible. In 2002, CIPAV researchers reported that the performance of the tubular digester does not depend on the use of polyethylene plastic or PVC geomembranes [83]. This design consists of a sealed bag connected at each end to an above-ground pipe, which enters through the pipeline, and the digestate exits at the other end and is deposited in a storage tank. A third pipe at the top of the cylindrical bag acts as the biogas outlet [84]. This household digester has a constant volume and operates at variable pressures to produce biogas [85].

Data on Colombian digesters installed and their characteristics were obtained via an online survey (using Google Forms) and oral communication (telephone interview). This survey was the first step in gathering information from RedBioCol partners, universities, foundations, and associations (n = 14 organizations) with experience with the AD process or digester installation. Additional information was also compiled from the websites of thirty-two regions in Colombia (known as departments). The keywords used were as follows: i) department name, ii) anaerobic digestion, iii) digester and iv) name of local environmental and governmental institutions. The obtained data are presented in Table 2. Information on 69% of the Colombian departments was received for this study, corresponding to 996 digesters currently installed. Reports published by the Colombian Environment Ministry indicated that approximately 5,700 digesters were established in the national territory [86]. Therefore, the data collected in this review correspond to a representative sample of the AD technology panorama in Colombia (confidence interval: 99%; margin of error: 4%).

The popularity of tubular household digesters has increased owing to their low cost, long shelf-life, simple design, and easy transportation. The tubular configuration of the digesters is 79%, and the remaining 21% corresponds to other models (batch and lagoon) and is without specifications.

The departments that stood out for the greatest number of digesters installed were Caldas, Cundinamarca, and Santander. Most of the digesters are low-cost tubular digesters because of the presence of organizations (such as RedBioCol and SENA) that cooperate with local rural communities, offering support and training on topics related to anaerobic digestion and digester installation. In contrast, some departments have a low or no number of installed digesters. Many of these territories are not electrically interconnected areas. In these territories, there is clearly an opportunity to take advantage of this technology by managing the organic waste generated through agricultural activities in each region.

The volume of digesters is highly variable, mainly due to the availability of organic wastes and the climate, with larger sizes in cold regions to increase the hydraulic retention time of the AD process. Another factor that determines the size of the digesters could be related to the budget available for installation.

Cow, horse, pig, buffalo, goat, and fish manures are the most important substrates used in Colombia, based on ~ 69% of the recorded digesters in this study. The remaining percentage of digesters use organic waste from other unspecified sources. Prior dilution of the substrates is required to ensure that the digester functions properly, avoiding clogging and scum formation on its surface and ensuring continuous flow operation. Previous studies on animal manure reported 1:3, 1:3, and 1:7 dilutions of manure:water ratio for bovine, porcine, and horse manure, respectively. These dilution ratios favored the methanogenic activity of the process [69].

Psychrophilic tubular digesters represent a simplified and successful technology in the country. Two examples of studies where this technology has been deeply analyzed in real conditions in Colombia are Castro et al. (2017) [44] and Jaime-Jaimes et al. (2021) [46]. In the first case, a 9.5m^3 total volume digester without stirring or heating devices, fed daily with cow manure and working at 23.5 ºC, produced biogas after 35 days from the start-up. The digester obtained a specific methane production (SMP) of 0.10 Nm^{3}CH$_4$/kgSV [44]. More information from this digester is found in section 4.3.4. When compared to mesophilic results, full scale digester fed with cow manure from [44] obtain halved SMP results (0.10 Nm^{3}CH$_4$/kgSV) than that reported by [87] for similar substrate at BMP tests at 36.5ºC, equal to 0.202 Nm^3CH_4/kgSV. This can be explained by the low HRT of the psychrophilic digester (35d) and because the digester was just beginning it operation and the AD microorganism could not be enough adapted to the psychrophilic conditions, as can be seen in the next case.

The other case is a 103 m^3 operational volume digester, without mixing of active heating devices, that operates in a 17.7 ºC mean slurry temperature [46]. The digester was fed with the swine manure mixed with water to clean the stables. The influent was around 4.16 m^3/d and the HRT was 25 days. The OLR was 0.52 kgVS/$m^3_{digester}$·d, the estimated SMP was 0.40 Nm^3CH_4/kgSV. The keg's key aspect of this digester was that has been operating for more than eight years. More information from this digester is found in section 4.3.5. Microbiological analysis revealed that the microbiota was adapted to psychrophilic conditions, thereby increasing methanogenic archaea content while decreasing bacterial populations. In this case, mesophilic results from [87] for swine manure BMP test at 36.5ºC reports 0.322 Nm^3CH_4/kgVS, do not show better results respect an eight years old psychrophilic digester. Although the HRT is reduced for psychrophilic conditions (25d), the 8 years old adapted microorganism looks to be able to produce similar or greater amounts of biogas than mesophilic.

From a technological point of view, there are room for action to improve those results, for example adding a previous process of pretreatment. An effective pretreatment can facilitate the degradability of complex organic molecules to convert them into smaller compounds to be used as substrates in conventional AD [88]. Thermal pretreatment of manure fibers with NaoH [89], or alkaline microwaving pretreatment [90] demonstrate that biogas production is increased. But adding most sophistication to the system, increase the investment, maintenance and operational cost of the digester, making it less accessible to medium and small farmers. Also, heating or energy conservation are important for improving the suitability of AD in cold regions [91]. When biogas is not used to generate electricity, so no waste heat is able from a Combined Heat and Power System (CHP), the biogas could be used to heat the digester. But, in Norway (temperature ranges from 1 to 13 °C) a burner was installed to heat the substrates to 37°C, being necessary to consume 85 kWh of the 105 kWh of the total energy produced by biogas [92]. So, if there are no waste heat from a CHP, the heating of the digesters, without increasing its complexity and investment cost, can be using passive solar heating design [26,28, 93].

Finally, low-cost tubular digester sacrificed more efficiency by more technological accessibility to farmers, balancing the lack of sophistication, with higher reactor volumes and passive devices for heating and mixing.

Table 2. Household digesters installed in Colombia, classified by departments.

Department	Number of digesters	Volume (m^3)	Substrates	Temperature	Type
Antioquia	11	12	75% pig manure (PM) and 25% horse manure (HM)	N/R	Discontinuous tank
	5	40	Cow manure, HM, and PM	-	-
	2	12	Unspecified manure	16.7 °C	Tubular
	1	N/R	Organic waste	N/R	
	1	20	PM	~15 °C	Tubular
Arauca	50	N/R	Unspecified manure	N/R	Tubular
	1	40	PM	18–24 °C	Tubular
Atlántico	1	40	Organic waste	18–24 °C	Tubular
	2	8–30	PM	18–24 °C	Tubular
Bogotá	3	40	Cow manure	25 °C	Tubular
	3	25	Organic waste (Not specified)	37 °C	-
Boyacá	1	32	PM	25 °C	Tubular
	1	40	PM	~15 °C	Tubular
Caldas	1	72	Cow manure	23 °C	Continuous flow
	250	variable	Organic waste (Not specified)	N/R	Tubular
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	1	21.6	PM and coffee leachate	N/R	Tubular
	5	8–40	Cow manure and PM or trout manure	N/R	Tubular
Casanare	2	14–16	Cow manure and PM	18–24 °C	Tubular
Caquetá	1	0.200	Cow manure	25–30 °C	Discontinuous tank
Cauca	1	300	PM	N/R	
	20	-	PM	N/R	Tubular
	1	40	Cow manure	N/R	Tubular
	4	14–40	PM and cow manure	15–24 °C	Tubular
Córdoba	1	20	PM	18–24 °C	Tubular
Cundinamarca	1	6	Cow manure	18 °C	N/R
	1	N/R	Organic waste (not specified)	N/R	Continuous flow tubular
	60	10.16	PM with water from the washing of the facilities, horse, bovine, and goat manure, and even free human waste	19–32 °C	Tubular

	200	12–28	PM, cow manure, fish manure, HM, and coffee leachate, depending on where it is installed	18–32 °C	Tubular
	10	9.6	Cow manure and PM	-	Tubular
	4	10	Cow manure and PM	20 °C	-
	1	1	Cow manure and PM	30 °C	Discontinuous tank
	67	6–40	Cow manure and PM or trout manure	15–24 °C	Tubular
Guajira	1	40	Cow manure	18–24 °C	Tubular
Huila	1	22.5	PM	N/R	
	1	47	Cow manure	17–31 °C	Tubular
Meta	21	0.20 - 10.73	60.7% PM 33.3% cow manure 6% human faeces	N/R	87% Tubular 13% discontinuous tank
	1	6	Fish manure	N/R	Tank
	1	10	Cow manure	35 °C	-
	6	10–40	PM and cow manure	18–24 °C	Tubular
Nariño	2	10–47	PM	25 °C	Tubular
	1	8	Cow manure		Tubular
Norte de Santander	11	N/R	Organic waste (Not specified)	N/R	-
Quindío	5	8	Coffee mucilage (CfM), grey and black water, and PM	18	-
	1	40	Cow manure	~15 °C	Tubular
Risaralda	4	14–40	PM, cow manure, and HM	15–24 °C	Tubular
Santander	1	N/R	Cow manure	N/R	Tubular
	14	N/R	Organic waste (Not specified)	-	-
	115	6	PM	21±6	-
	6	8	PM and cow manure	25	-
	6	6; 8; 10; 100	Mix whey, HM, cow manure, and PM	15; 18; 23; 30	-
	5	8	CfM and manure (type not specified)	22	-
	3	8	PM	28	-
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	8	N/R	Organic waste (Not specified)	N/R	Tubular

	5	8–40	Cow manure and PM or buffalo manure	15–24 °C	Tubular
Tolima	10	N/R	-	-	-
	25	6	Cow manure and PM	20 °C	-
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	1	40	Cow manure	N/R	Tubular
	2	6–30	Cow manure and PM	18–24 °C	Tubular
Valle del Cauca	1	40	PM	N/R	Tubular
	1	0.190	Organic waste (Not specified)	N/R	-
	1	20	Water- CfM	25 °C	-
	7	14–40	Cow and pig manure	15–24 °C	Tubular
Vichada	1	12	Fish manure	N/R	Tubular
	1	8	Organic waste (Not specified)	N/R	-
	1	12	PM	N/R	-
	1	20	Organic waste (Not specified)	N/R	Tubular
	5	8–20	Cow manure	18–24 °C	Tubular

Prior dilution of the substrates is required to ensure that the digester functions properly, avoiding clogging and scum formation on its surface and ensuring continuous flow operation. Previous studies on animal manure reported 1:3, 1:3, and 1:7 dilutions of manure:water ratio for bovine, porcine, and horse manure, respectively. These dilution ratios favored the methanogenic activity of the process [69].

Regarding the quality of biogas, in terms of methane content, it could be inferred from previous studies on tubular household digesters using different substrates that it remains above 40% and achieves an increase with temperature from psychrophilic conditions (40–65%) to mesophilic (60–70%) [15,25]. This makes it possible to cover the fuel needs for thermal energy, cooking and heating, mainly, and in some cases, to supply mechanical energy in engines of agricultural machines. Small-scale biodigesters (8-15 m^3) produce around 3 m^3/day and allow to meet the energy requirements in cooking food for 5-8 people. Medium-scale biodigesters (>40 m^3) deliver approximately 8 m^3/day, and biogas is used to sterilize milking machines and heat piglets. Besides, in the case of some small-scale biodigesters, H_2S is removed through a packed iron oxide biogas filter. However, on a medium scale, there is an obstacle to using biogas in other more specialized applications for which advanced desulfurization technologies [94] or low-cost natural materials [95] are required in the purification and upgrading of biogas. Since the technology has come out of the laboratory directly to rural areas, several risks have been identified, among them: CO_2 emissions, CH_4 and NH_3 explosion, high concentrations of H_2S cause negative effects on the water, it is very toxic irritant and can inhibit respiration [96]. However, all these risks are currently not considered.

4.2 Large-scale AD technology development

In Colombia, the beginning of the AD implementation on a large-scale date back to 1982, when the first large-scale digester for wastewater treatment was installed (Cañaveralejo Plant, Cali). After the success of the first pilot plant, two larger projects, financed by the

Dutch Cooperation, were established: the Vivero Plant by the Empresas Públicas Municipales de Cali (EMCALI) and the Rio Frío plant by the Environmental Authority Corporation for the Defense of the Bucaramanga (CDMB) [97].

Since then, AD has been implemented on a large-scale in both the public and private sectors for treating sewage or waste treatment generated in their production processes. Mainly two types of digester configurations have been used in the country: the Upflow Anaerobic Sludge Blanket (UASB) and the covered lagoon type digesters. The UASB reactor was developed in the 1970s in the Netherlands, and it is widely used worldwide, including in Colombia, on a large-scale owing to its technical and economic advantages, the possibility of treating granular sludge, excellent settling abilities, extremely low sludge volume, and improved separation [98]. The UASB reactor is used in wastewater treatment plants as an initial process and is the most technically and legally developed reactor in Colombia [99]. On the other hand, the covered lagoon is utilized for the treatment of animal manure. This system consists of a lagoon completely covered and hermetically sealed with a high-resistance PVC or polyethylene geomembrane. A covered lagoon operates at an ambient temperature without the requirement for heat [27]. Table 3 presents a large-scale review of the digesters installed in Colombia.

Table 3. Large-scale digesters installed in Colombia, classified by Department

Department	Company	Number of digesters	Volume (m^3)	Substrates	Type
Antioquia	Grupo EPM - PTAR Bello	6	-	Sludge	UASB
	Colanta	1	-	effluents from dairy production	UASB

Atlántico		1	2500	-	Covered lagoon
Bogotá	Doña Juana	-	-	Municipal organic waste	UASB
	Salitre	-	-	Sludge	UASB
Cauca	Palmar Santa Elena	1	500	Effluents from palm oil and biodiesel extraction	
	Palmeiras	1	7000	Effluents from palm oil and biodiesel extraction	
César	Indupalma	1	-	Effluents from palm oil and biodiesel extraction	-
Cundinamarca	Alpina	1		Effluents from dairy production	

Meta	Aceites Manuelita	2	19 000		-
	Palmeras del llano	1	750[3]	Effluents from palm oil and biodiesel extraction	-
Nariño	Palmar Santa Elena	1	500	Effluents from palm oil and biodiesel extraction	
		1	23 642	Cow and pig manure	Tubular
	Palmeiras	1	7000	Effluents from palm oil and biodiesel extraction	
Santander	Indupalma	1	16 000	Effluents from palm oil and biodiesel extraction	

	Bavaria	1	-	Effluents from brewing plant	UASB
	El Carrasco	1	60	Leachate from landfill of municipal wastes	UASB
	Río Frío Bucaramanga	1	6 600	Sludge	UASB
Tolima	-	1	1500	Pig manure	Covered lagoon
Valle del Cauca	PTAR Cañaveralejo EMCALI	4	-	Sludge	UASB
	PTAR El Vivero	1	1000	Sludge	UASB
	Bavaria Valle	1	-	Effluents from brewing plant	UASB
	Ingenio San Carlos	1	-	Effluents from the	-

	sugar industry

The large-scale implementation of AD in Colombia is represented by municipal wastewater treatment plants, as well as treatment plants for wastewater from palm oil, milk, and breweries. In some of these industries, the biogas produced is used to meet the energy needs of their production processes. However, in most cases, the percentage of gas use is only approximately 30%, while the other 70% is burned in torches to convert methane into CO_2 and expel it into the environment.

4.3 Case studies

4.3.1 El Común

El Común, a non-governmental organisation, is a pioneer in promoting biogas in Colombia. The contributions made by this organisation include installing productive units that donate two pigs to each rural family, installing a garage and a forage orchard, and installing and assembling a household digester (fig. 2). To finance these projects, El Común has the support of international entities such as Green Empowerment and Proyectos para un Futuro Mejor. According to the surveys carried out, El Común has installed 150 small-scale household digesters (6 m^3) until date, of which 115 are in operation, becoming one of the most successful cases in Colombia for the promotion and implementation of AD technology. Beneficiaries participate actively in installing the digester through community workdays and receive permanent training on various aspects such as animal feeding from forage, use of effluents, and technical management of the digester, among others.

Figure 2. Household digesters installed by El Común.
Image taken from the official website of El Común: www.elcomun.org

A similar case is ASPROINCA (Association of Indigenous and Farmers of Riosucio), which has installed more than 300 low-cost digesters. The association members can access plastic tubular digesters and are financed through revolving funds [31].

4.3.2 *Doña Juana*

A successful example of AD implementation on a large-scale and the use of biogas for electric power generation is the Doña Juana landfill in the city of Bogotá, one of the most important projects in Colombia. The project is structured in three plants, depending on the availability of connection points granted by the local energy network operator and approved by the UPME. Here, biogas is obtained from leached urban solid waste from the city of Bogotá and some neighbouring municipalities, and electrical energy is generated from the biogas obtained. With the implementation of this plant, it has been possible to achieve 35% compliance with the goals for Colombia agreed at the United Nations Conference on Climate Change 2015 (COP 21).

4.3.3. Experiences in Cumbal, alongside Ecuador border

Cumbal is a rural municipality with altitudes ranging from 1,000 to > 4,500 m and a mean ambient temperature ranging from 25–10 °C. In this municipality, the main population is indigenous, and the most common household activity is dairying and raising cattle and guinea pigs. Cumbal habitants are interested in solving the problems caused by cooking with firewood, such as deforestation and diseases, and exposure to smoke. An alternative to fulfil the energy requirements of Cumbal habitants is to carry out the AD process with the main residues generated: dairy wastewater, cattle, and guinea pig manure. With the support of the National University of Colombia, some research has been conducted to implement a household digester.

The low-cost tubular digester was arranged in a polyethylene cylindric bag (6.5 m length and 6 m^3 effective volume) covered with a greenhouse. Additionally, a reservoir was fitted to store 4.5 m^3 of biogas. The load was composed of a blend of 20 kg of manure (70% cattle; 30% guinea pig) and 60 L of dairy wastewater. This initiative provided important results; it was found that co-digestion of cattle and guinea pig manure and dairy wastewater increased the biogas yield 2.56 times compared with that obtained with cattle manure mono-digestion. The biogas produced was approximately 0.9 m^3/d with a quality of approximately 61% CH_4–69% CH_4. However, researchers have shown some operational problems owing to a lack of users. Thus, it was concluded that the correct operation of the digesters depends, to a large extent, on the commitment to system management.

***4.3.4** Marcella Farm: a family experience*

A traditional Colombian peasant family that used firewood for cooking installed a low-cost tubular digester built with tubular polyethylene, with an effective length of 7.5 m and a total digester volume of 9.5 m^3. The substrate was a mixture of bovine manure and rainwater in a 1:3 ratio. The manure was generated from three cows that were housed 65% of the day. The daily treated manure was around 51 kg, representing an organic load of 0.7 kg $VS/m^3_{digester}*d$ (hydraulic retention time of 35 d). Owing to the installation of this digester, 0.85 Nm^3 biogas/d was generated (with 65.6% of CH_4) and used for cooking. In this way, the users generated enough energy to cook food for five people, saving 50 USD per month. Additionally, the digestate (around 0.14 m^3/d) presented high nutrient content, which was used for land spread [44].

4.3.5. "La Loma" farm digester. Pig manure treatment

La Loma farm is in the Boyacá department (altitude of 2,963 m and latitude of N 6 °27'45.0" W 72 °24'43.0"). This farm is located near the El Cocuy National Natural Park, and the average zone temperature is approximately 12 °C. Since 2012, the "La Loma" farm has focused its livestock activities on improving its residues disposition. In this context, it was decided to implement a pig manure anaerobic digester. A 30 m polyethylene anaerobic digester (103.1 m^3 operational volume) was covered with a polyethylene greenhouse for environmental protection and to improve internal temperature conditions.

The digester treats the manure produced by 255 animals at a 1:6 ratio mixture of dung and free-range wash water. The blend corresponds to a flux around 4.16 m^3/d (HRT = 25 days). In particular, the digester has been operating for more than eight years. In 2021, Jaimes-Estévez *et al.* [46] monitored this digester for five weeks to determine the performance of a psychrophilic rural digester. In this study, we assessed the thermal performance and microbiological and biochemical status of the digester. As a result of this experience, researchers found that greenhouse protection does not improve the internal temperature, and an alternative to trench insulation should be used. Microbiological analysis revealed that the microbiota adapted to psychrophilic conditions, thereby leading to an increase in methanogenic archaea content while decreasing bacterial populations. This adaptation resulted in an increase in hydrolytic and fermentative processes. The acclimatization and adaptation of the microorganisms allowed good digester performance to reach a high methane production of approximately 0.40 Nm^3CH_4/kg VS.

5. Colombian legislation and policies for biogas use

5.1. *Regulatory entities*

In Colombia, the Ministry of Mines and Energy (MME) and the Ministry of Environment and Sustainable Development (MESD) are the main governmental institutions that standardize and regulate public policies regarding the generation and use of energy and environmental care. The MME is supported by various governmental agencies, such as the Mining Energy Planning Unit (UPME) and the Institute of Planning and Promoting Energy Solutions in Non-Interconnected Zones (IPSE), which are in charge of capacity planning and support of policymaking, and the Energy and Gas Regulation Commission (CREG), which regulates power and gas tariff s.

The MME and MESD consider biogas as a non-conventional energy source and an alternative for mitigating climate change. On the other hand, the IPSE considers biogas as an alternative and energy solution for rural areas with no electricity supply, representing approximately 60% of Colombian territory. Therefore, the IPSE promotes and implements projects in the most remote areas of Colombia for the use of biogas technology in kitchens as a replacement for firewood and electricity generation. The broad reasons allow us to support this decision. This highlights that the production of biogas from different biomasses is an economically sustainable alternative that helps mitigate climate change and improve the quality of life of the communities. These projects also contribute to the income of the productive chains and promote caring for the environment through energy use from waste.

In Colombia, biogas production from solid waste in landfills began in the mid-80s. However, biogas generation from waste is unregulated in terms of production, transport, commercialization, and distribution. In 2009, the CREG published the first regulation applicable to biogas [100]. It established a “supervised freedom” figure for public service companies for biogas management through isolated networks only and exclusively for industrial users. This regulation prohibited the commercialization of biogas for residential users and the mixing of natural gas or liquefied petroleum gas with biogas.

The timeline of biogas regulations in Colombia is presented in Table 3. Since 2009, regulatory entities collaborating with the Colombian government began to combine efforts to improve regulations as needed. Consequently, some resolutions were issued by the CREG in 2012 [101,102]. Finally, in 2014, the Colombian government established a legal framework (Law No. 1715,2014) and tax instruments to promote non-conventional energy sources [88].

Table 3. Timeline of biogas regulations in Colombia.

Year	Law
2009	***Resolution CREG-056.*** This was the first regulation applicable to biogas. This regulation gives public service companies a figure of "supervised freedom" for distributing and commercializing biogas through isolated grids, only and exclusively for industrial users.
2012	***Resolution CREG-135:*** Regulation applicable to the domiciliary public services of fuel gas with biogas adopted.
	Resolution CREG-079: Regulation applicable to domestic public service of fuel gas with biogas produced by decomposition wastes.
2014	***Law 1715:*** Legal framework and the tax instruments for promoting, implementing, and developing non-conventional energy sources.
2015	***Decree 1077:*** Requirements for the viability of biogas as an energy recovery alternative and the need to monitor biogas composition.
2016	***Resolution CREG-240:*** This resolution repeals Resolution CREG 135 of 2012. The minimum quality requirements and safety conditions were established for the biogas and biomethane used in the domestic public service.
2017	***Decree 1784:*** Establishes in more detail the final disposal of solid waste, its management in landfills, and the requirements for its energy use, including the use of biogas produced.

In 2015, Decree-Law No. 1077 [103] was established, showing more details about the final disposal of solid waste and the requirements for its use as raw material to produce energy, including biogas. It is worth noting that there were no significant changes in the use and monitoring of biogas compared to those in the previous decree.

In response to the lack of regulations related to quality and safety of biogas commercialization, especially for domestic use, in 2016, the CREG established Resolution No. 240 [104], in which the standards applicable to domestic public service of fuel gas, including biogas and biomethane, were adopted. One of the main provisions established by this resolution is related to biogas quality and its monitoring (calorific value, Wobbe index, methane concentration, hydrogen sulfide, and carbon dioxide, among others).

5.3. Financing mechanisms and incentives

In Colombia, although the monetary funds for financing alternative energy projects are still somewhat limited, public funds are sponsored by the state and funds from international agencies. The first fund was created in 2014 through Law No. 1725, which establishes the Non-Conventional Energies and Efficient Energy Management Fund (FENOGE), financed by public or private national organizations and multilateral or international funding organizations. In addition, tax reductions and incentives are created for those organizations that invest in the research and development (R&D) of unconventional energy sources.

Regarding the promotion of research, this law dictates some provisions that promote research, technological developments, and innovation in non-conventional energy sources and their subsequent applications and adoption in the national energy system. To manage this initiative, the national government empowers regional autonomous corporations and local offices to include in regional development plans, measures that promote scientific research on alternative energy sources, which must be framed in national and global energy policies.

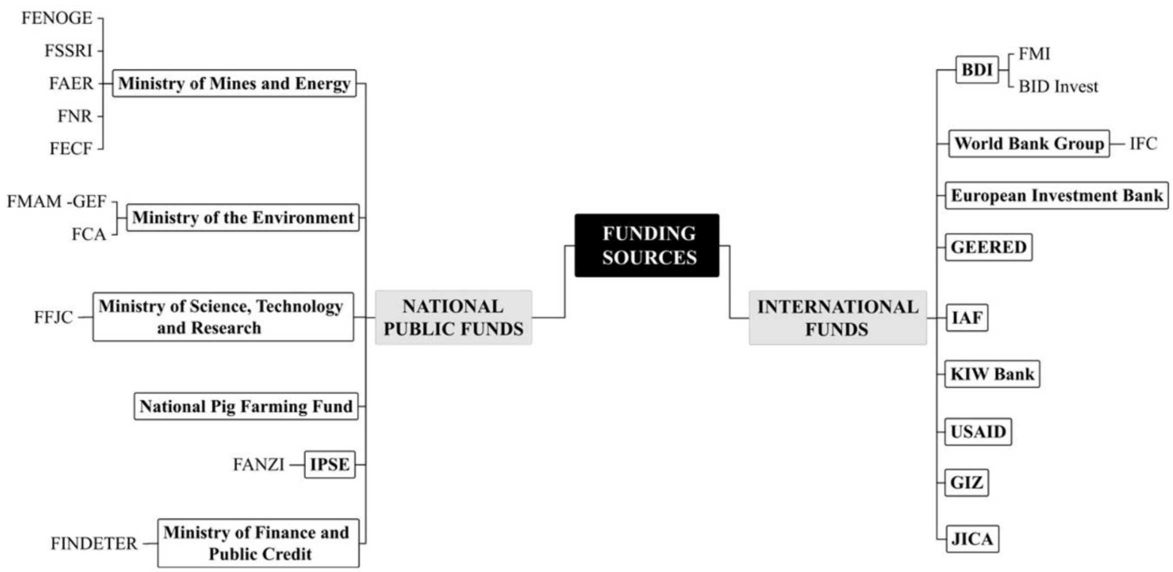

Figure 3. Funding in Colombia for the implementation of projects for the use of biogas.

The incentives, support programs, and reduction in taxes offered by the national government in this law have prompted some public and private companies to shift their interest toward the utilization of non-conventional energy uses, within which the use of biogas is generating great interest.

The Global Environment Facility (GEF), created in 1991 by the governments of 182 countries, international institutions, non-governmental organizations (NGOs), and the private sector, is the largest financial resource for projects to improve the global environment. Ten agencies comprise the United Nations Development Program (UNDP), United Nations Environment Program (UNEP), World Bank, Food and Agriculture Organization of the United Nations (FAO), United Nations Industrial Development Organization (UNIDO), African Development Bank (AfDB), Asian Development Bank (ADB), European Bank for Reconstruction and Development (EBRD), Inter-American Development Bank (IDB), and International Fund for Agricultural Development (IFAD).

In Colombia, financing investment plans, programs, and projects in energy infrastructure in non-interconnected areas (ZNI) are supported by the Financial Support Fund for the Energization of Non-Interconnected Zones (FANZI). This fund system was created by Law

No. 633 of 2000 [91] and regulated through Regulatory Decree No. 1124 of 2008 [105]. Currently, it is managed by the Ministry of Mines and Energy through the IPSE.

The research investments are focused on the National Fund for the Financing of Science, Technology, and Innovation Francisco José de Caldas (FFJC). FFJC is a financial mechanism that allows the Ministry of Science, Technology, and Innovation to finance the development of different science, technology, and innovation projects, among which can be highlighted the implementation of unconventional energy sources. Likewise, other public national funds exist to finance the projects aimed at implementing energy generation from unconventional sources that are managed by different national ministries. It is worth noting that there is a specific national agency for biogas production through pig manure, named the National Pig Farming Fund, which provides technical advice and finances projects related to this topic.

It should be noted that RedBioCol brings different actors in Colombia to promote the development of alternative energy and channelize resources from diverse public and private funds to implement AD as a technology for energy generation from organic waste.

Different international agencies are currently participating in financing renewable energy projects in Colombia. These entities are mainly the International Development Bank (BDI), World Bank Group, European Investment Bank (EIB), German bank Kreditanstalt für Wiederaufbau (KIW), the German Society for International Cooperation (GIZ), the United States Agency for International Development (USAID), Inter-American Foundation (IAF), Global Energy Efficiency and Renewable Energy Fund (GEEREF), Japan International Cooperation Agency (JICA), and Green Empowerment.

Finally, in Colombia, there are some credit programs to help establish low-cost digesters in rural areas. These programs are focused on farmers and are proposed by mixed banks such as FINDETER, the Fund for the Financing of the Agricultural Sector (FINAGRO), and private banking entities.

5.4. Environmental criteria and regulations

It has been estimated that biogas technology could potentially reduce emissions of methane (by 4%) and nitrous oxide, thereby mitigating global warming [20].

The MESD has implemented the Nationally Appropriate Mitigation Action (NAMAS) and sustainable development goals promoted by the United Nations. The implementation of biogas production is encouraged in different national policies, such as the National Policy for the Comprehensive Management of Solid Waste, CONPES No. 3874 of 2016 [106], which aims to implement waste management strategies that contribute to climate change mitigation and the promotion of a circular economy. Biogas production in sanitary landfills has been established as an alternative to valorization of urban solid waste. This strategy is also planned in the National Climate Change Policy [107], which presents opportunities to link the economy and climate change. It shows different strategies for rural, urban, mining energy, infrastructure development, and ecosystem conservation. Another policy aimed at this objective is the Green Growth policy [108], which establishes productivity and economic competitiveness objectives for 2030 in conjunction with the sustainable use of natural resources, climate protection, and social inclusion. Green growth promoted by this policy directly impacts the national objectives of building sustainable cities and communities, responsible production and consumption and achieving affordable and non-polluting energy sources framed within the functions of the IPSE.

These current policies are part of the 2014–2018 development plan. Three main objectives have been established: sustainable low-carbon growth, protection and assurance of natural capital, and vulnerability reduction to the risk of disasters and climate change. Likewise, this plan was adopted in 2015 by Law No. 1753 [109].

The Ministry of the Environment and the National Pig Farming Fund, Pork, Colombia, promotes the implementation of digesters for biogas production as a renewable energy alternative mainly for thermal use in rural areas, especially in non-interconnected areas. In addition, they created the Biogas Guide for the pork sector in Colombia, which proposes for small and medium producers to develop a sustainable pork production chain through the implementation of these energy alternatives. This guide contains technical and economic details for implementing these technologies, as well as financial and tax incentives that can be accessed, becoming a document of great support for the producer at different scales to seek sustainable production [86].

The development of alternative energy sources also involves certain environmental aspects, which are considered in Law No. 1715 [110]. Regarding this issue, the Environment and Development Ministry, National Environmental Licensing Authority (ANLA) and regional autonomous corporations have been assigned the task to formulate the guidelines and procedures that allow the evaluation and follow-up of possible environmental and energy impacts that may occur with the use of these new energy sources. Furthermore, the government is committed to developing new rules and regulations for emissions and discharges resulting from the use of these new energy alternatives. Unfortunately, policies for the implementation of low-cost digesters do not exist. Therefore, there are no regulations for low-cost digesters, and no licenses are issued for this type of project.

6. Barriers, opportunities, and challenges

Despite AD development in Colombia, some barriers limit the promotion and implementation of this technology in the country. The main limitations are as follows: obtaining resources to cover investment costs, lack of experience with biogas projects by the funders, perspective of the digestate market (uncertainty regarding the quality, use, and commercialization of the digestate in the country), and lack of regulation for the integration of biogas to electricity or natural gas networks. A significant barrier is the lack of understanding of the benefits and viability of this technology among the population, stakeholders, and even academia.

In developing countries such as Colombia, AD and biogas regulations are generally transferred from developed countries with other industrial and technological realities, more than a local response to local reality. In rural areas, where biogas plants have been installed for decades, and there is room for improvement, there is no government policy to reinforce this decentralized, small-scale, renewable energy technology as low-cost tubular digesters.

Currently, there is a disarticulation among academia, government, industry, and the communities. Although progress has been made in research at the laboratory level, it has not been easy to translate research progress into real-life applications despite favorable experiences. The lack of funding resources also strongly influences this aspect. Implementing AD on a large-scale is expensive, and it is difficult to highlight its advantages over other renewable energy sources for electricity production, as seen in Europe [2]. Nevertheless, biogas plants have an opportunity if they are linked with additional benefits that renewable energy technologies do not offer, such as waste treatment services and nutrient recycling for agriculture.

The AD R&D of organic residues in Colombia has mainly covered laboratory-scale studies, and small-scale digesters are typically used to produce biogas for heating and cooking purposes (see Table 3). Commercial digesters are used for electricity production to a lesser extent. Several studies have demonstrated the advancement of AD technology in Colombia and revealed the opportunities and challenges in the next few years [21]. In Colombia, the Ministry of Agriculture and Rural Development (MARD) divides the productive sectors into chains, among which the agricultural sector accounts for 7% of the country's GDP [98]. Different sectors have their demands regarding the management and use of waste and by-products generated [99]; hence, the government is looking for solutions to these problems.

The integration of AD in sustainable agriculture is a topic of interest from different points of view in Colombia. From an energy point of view, Preston and Rodriguez [111] estimated the energy return on energy investment (EROEI) of an integrated medium-scale farm that combines sugar cane and pig production with gasification and anaerobic digestion for energy production from organic wastes. The results revealed an EROEI of 8:1 ratio, indicating that eight energy units are obtained per energy unit introduced in the system (considering the energy associated with human labor and animal feed purchase), which is a good alternative to conventional biofuel production. An early publication by Chará *et al.* [112] in 1999, commented before, is also linked to the performance of a full-scale tubular digester in an integrated system for farm wastewater treatment. In 2009 [113] and 2011 [114], Rodriguez *et al.* published results comparing anaerobic digestion effluent from a low-cost tubular digester and biochar derived from gasification of sugarcane bagasse and native microorganisms collected from the same farm. The findings showed that the combination of biochar and AD effluent positively affected green biomass growth even better in soils without organic matter. The incorporation of native microorganisms improved these results. These results indicate the potential of using AD effluent mixed with biochar for increasing soil fertility and soil restoration. Therefore, sustainable agriculture in integrated farms can take advantage of energy and nutrient recovery while treating agricultural waste through low-cost digesters.

Colombia is one of the largest vegetable oil producers of palm oil worldwide. Currently, the planted area of palm oil exceeds 500 thousand hectares in the national territory [115]. Arrieta *et al.* [116] demonstrated huge potential for increasing the power efficiency of palm oil mills by generating biogas from the anaerobic treatment of wastewater and its conversion into electricity using CHP systems. The use of palm oil mill effluents in biogas production is an alternative that positively impacts all biorefinery concepts [117]. However, Ramirez *et al.* [118] argued that few mills carry out biogas capture, and only some generate electricity from biogas. Therefore, there is a possibility of technology transfer and optimization of the palm oil sector should be considered.

Rice production is also of great importance for the country since the crop occupies 350 thousand hectares, and its entirety is for internal consumption [119]. The AD of rice straw was tested as an alternative for treating this sub-product of paddy rice harvest to mitigate the environmental impacts caused by the illegal burning of rice straw in rural fields [120]. The effect of the inoculum/substrate ratio (I/S) on the AD of rice straw carried out in batch reactors at room temperature (25–27 °C) was studied. The results demonstrated a high biogas production (410 L/kg VS) at an 0.8 I/S ratio, with a methane content of over 70%. Furthermore, it was shown that using a natural microbial consortium as rumen fluid for lignocellulosic material degradation could be an effective and promising option. However, the study was conducted at the laboratory level; therefore, it is necessary to develop a model that involves scaling the technology.

AD integration models have been developed for various productive sectors. Non-centrifugal cane sugar (NCS) is one of the main products of Colombia since it stands out as the second-largest producer in the world after India, with 1.3 Mt of NCS production per year [121]. Mendieta *et al.* [122] developed a theoretical model for managing waste from the NCS agro-industrial sector. Similarly, Escalante *et al.* [65] developed a model for the dairy sector, including the production of biogas and struvite in the integration of AD technology. The next stage should consider validating these models in a real environment.

Ortiz *et al.* [123] studied the sustainable management of peel residues in small-scale orange juice industries. The life cycle assessment (LCA) established that anaerobic digestion with the recovery of the digestate for reuse in the cultivation of oranges is an environment-friendly option. However, higher costs are incurred than in the scenario where waste is incinerated. At this point, low-cost AD technology for the industry should be tested. Garfi *et al.* [48] assessed the environmental benefits of implementing low-cost digesters in small-scale farms in Colombia using the LCA methodology. Results showed that the implementation of digesters reduced considerably (by up to 80%) the potential environmental impacts associated with manure handling, fuel, and fertilizer use in small-scale Colombian farms, due to the reduction of liquefied petroleum gas and synthetic fertilizer use, which were replaced by biogas and the digestate. Similar benefits were observed with a low-cost digester using cattle manure as a substrate for use in rural areas for biogas production, with improved digestate quality [44].

In contrast, Mendieta *et al*. [124] evaluated the environmental benefits of implementing low-cost digesters to valorize agro-industrial waste in the non-centrifugal sugarcane sugar sector. The environmental impact of freshwater eutrophication and marine eutrophication showed a reduction of 87.6% and 99.4%, respectively, compared to the current scenario. Thus, by treating organic waste and wastewater on-site while producing bioproducts (*i.e.*, biofuel and biofertilizer), low-cost digesters could boost the circular bioeconomy in the NCS production sector.

Colombia offers a wide diversity of agricultural and livestock products because of its location in the tropical zone of the world. Consequently, a large amount of organic waste is generated throughout the year. On the other hand, Colombia has government support (MARD, MME, MESD) and human resources (universities, entities that provide agricultural technical assistance services, among others) to develop research projects focused on the mitigation of the environmental impact due to the generation of such wastes. Accordingly, some of the resources have been allocated to the promotion of anaerobic digestion technology.

There are several challenges that future research on AD in Colombia should focus on better understanding the reality of farmers and rural areas to link the investigation to the real-life necessities. Research must go hand in hand with the pillars of sustainability, which poses a dilemma with the agro-industrial sector, such as palm oil. At the social level, technology transfer can be expanded to achieve greater adoption of technology. Agricultural sectors remain unaware of anaerobic digestion or do not recognize the benefits of technology, which is why a mass adoption strategy is required. Regarding the environmental pillar, it is essential to investigate the benefits of anaerobic digestion for a certain sector, considering the current management of residual biomass and climatic conditions. The latter is important for the design and implementation of digesters. Finally, from the economic component perspective, it is necessary to adapt low-cost digesters to the conditions of each sector. Despite advances in R&D, policies are needed in Colombia to regulate the biogas chain, including production, transportation, commercialization, distribution, and its use, which would help AD position itself as a technology for energy production for the country.

7. Discussion and lessons learned

Anaerobic digestion technology has been promoted in recent decades, depending on the economic status of the regions. In developed countries, AD technology is positioned on an industrial scale to generate electricity for the grid through biogas combustion and is currently used for the production of biomethane [2]. However, in impoverished countries, small and medium-scale technologies are widespread and integrated into farms to use the biogas for thermal and cooking energy sources, wastewater treatment, and nutrient recycling. An example of this can be found in Latin America, [15] Africa [8], and for India [11]. Finally, most low-cost digesters in developing countries are installed on household farms, where the integrated agricultural system is working (combination of livestock and crops).

Evidence shows that most digesters installed in Colombia are unheated systems, similar to those in many other developing countries [7,15,125]. For instance, UASB for urban wastewater treatment, lagoon for large agricultural waste generator industries (palm oil or pig slots), and low-cost tubular digesters for medium and small farmers.

These have main effects on regulations and research. In terms of regulations, developing countries tend to implement rules adapted from developed countries with industrial AD, neglecting the local small and medium AD technologies being implemented without appropriate and adapted regulations. In the case of Colombia, regulations are focused on the distribution of biogas in an insulated grid, biogas composition, and safety conditions for biogas distribution. Those are more related to developed countries' needs and biogas sector development [2] than to Colombia's reality, while most of the digesters in the country produce biogas for in situ consumption, usually as cooking fuel.

From a research perspective, most digesters implemented in developing countries work at psychrophilic temperatures [2,15,125]. Furthermore, the methodologies (such as the BMP test [126]) and knowledge focus on mesophilic conditions according to the needs of developed countries that use to heat digesters. Therefore, there is a lack of research on psychrophilic AD that the impoverished countries have to cover, despite a lack of funding research.

Biogas technology suppliers in Colombia have limited capacity to transfer laboratory research to full-scale systems, unlike the biogas sector in developed countries. Academic researchers have covered this gap by focusing their studies on the performance of full-scale digesters. In addition, most methodologies and protocols in AD are for mesophilic conditions (heated digesters). However, the real-life setup in developing countries includes psychrophilic conditions (unheated, low-cost digesters). Hence, in this context, research on low-cost digesters has overcome the lack of proper laboratory-recognized psychrophilic methodologies.

The experience in Colombia is that low-cost AD biogas technology became widespread slowly but continuously, even without proper regulations or direct government support beyond recommendations or limited experiences. National and international NGOs promote this process, and local organizations such as RedBiocol drive the share of experiences and spread low-cost digesters in the country. As the universities have joined the RedBiocol and the research has been scaled-up, low-cost digesters is beginning to cover the gap in knowledge of long-term psychrophilic AD.

8. Conclusions

The main objective of this review was analyzing the current state of anaerobic technology, barriers, and opportunities in developing countries such as Colombia. Research and development on AD have been evolving in recent years, highlighting the interest of academia and industrial sector and increasing the implementation of this technology. Although AD technology has been in use since many years, there are still significant gaps in knowledge about its implementation and performance under long term psychrophilic conditions in rural areas, where the technology was initially developed through trial and error.

Research has focused on studying AD performance, using diverse substrates and local inoculum at the laboratory level to promote the sustainability of different agricultural sectors. The review carried out in this study found that manure from various livestock farms (mainly cow, horse, pig, buffalo, goat, and fish manure) is the most important substrate used in Colombia (69%), followed by organic wastes from other unspecified sources (31%). The main characteristics of the inoculum are its origin, VS content, and SMA. The main sources of inoculum used are stabilized cow manure and pigs.

Reports published by the Colombian Environment Ministry indicate that currently, there are approximately 5,700 digesters installed in the country. The departments with the highest number of digesters are Caldas, Cundinamarca, and Santander. The most commonly used type of digester in Colombia is the low-cost tubular configuration (79%). The remaining 21% correspond to other models (batch and lagoon) and are not specified.

Even though anaerobic digestion is considered a promising technology in Colombia, the AD sector faces critical challenges, such as feedstock pre-treatment using low-cost technologies, developing a sustainable market for biogas and digestate, and process safety in small and medium digesters. As well, the development of policies for renewable energy sources has been identified, and it is necessary to structure policies focused on AD to implement the technology throughout the country.

Finally, academic research is approaching the study of full-scale psychrophilic digesters, the vast majority of installed digesters in Colombia, as in the rest of developing countries.

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Current understanding and perspectives on anaerobic digestion in developing countries: Colombia case study

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Abstract

Anaerobic digestion (AD) technology has become increasingly important due to its contribution to sustainability and a circular bioeconomy. While AD technologies are widespread in developing countries, developed countries have mainly driven research. The aim of this research is to analyze the biogas sector development from the point of view of a developing country like Colombia. AD research ranges from laboratory mesophilic AD to psychrophilic full-scale digesters, which are intergrated with household farms as a thermal energy source for cooking, nutrient recycling for agriculture, and waste management. Research on agricultural waste substrates, inocula, and co-digestion has dominated the Colombian publications, while full-scale digesters performance research is incipient. A survey of installed digesters collected information about 996 systems and found that 79% were psychrophilic low-cost tubular digesters. Regulations for biogas were reviewed, and it was found that they are not adequate for low-cost digesters and are inherited from developed countries, ignoring the national context. Five case studies are presented on the characterization of AD technology experiences, analyzing barriers and opportunities for the technology. National networks that include farmers, NGOs, and academia are driven slowly by Colombia’s widespread AD technology, mainly on small-to medium-scale farms.

Highlights:

- Half of the Colombian AD publications are from the last three years.
- 79% of the digesters are low-cost and run under psychrophilic conditions.
- Mesophilic AD research on substrates, co-digestion, and inoculum dominates.
- There is a lack of regulation, support, and psychrophilic AD research.
- Multidisciplinary networks drive the spread and research of low-cost digesters.

Keywords

Biogas; developing country; renewable energy; household digester; policies; psychrophilic anaerobic digestion

Word count: 9440

List of abbreviations

AcoD: Anaerobic Co-Digestion

ADB: Asian Development Bank

AD: Anaerobic Digestion

AfDB: African Development Bank

ANLA: Autoridad Nacional de Licencias Ambientales (National Environmental Licensing Authority)

ASPROINCA: Association of Indigenous and farmers of Riosucio

BBIW: Bottled Beverage Industry Waste

BDI: International Development Bank

BM: Bovine Manure

BMP: Biochemical Methane Potential

CfM: Coffee Mucilage

CHP: Combined Heat and Power system

CIPAV: Centre for Research on Sustainable Agricultural Production Systems

CIR: Cocoa industry residues

CkM: Chicken manure

CREG: Comisión de Regulación de Energía y Gas (Energy and Gas Regulation Commission).

CW: Cheese Whey

DWS: Domestic Wastewater Sludge

EBRD: European Bank for Reconstruction and Development

EIB: European Investment Bank

EROEI: Energy Return on Energy Invested

FAER: Fondo de Apoyo Financiero para la Energización de las Zonas Rurales Interconectadas (In English: Financial Support Fund for Energization of the Interconnected Rural Zones).

FANZI: Fondo de apoyo financiero para la energización de las zonas no interconectadas (In English: Financial support fund for Energizing non-interconnected Zones)

FAO: World Bank, Food and Agriculture Organization of the United Nations

FECF: Fondo Especial Cuota de Fomento (In English: Special Fund for Development Fee)

FENOGE: Fondo de Energías No Convencionales y Gestión Eficiente de la Energía (Non-Conventional Energies and Efficient Energy Management Fund).

FFJC: Fondo Nacional de Financiamiento de la Ciencia, Tecnología e Innovación Francisco José de Caldas (In English: National Fund for the Financing of Science, Technology and Innovation Francisco José de Caldas).

FINAGRO: Fund for the Financing of the Agricultural Sector

FINDETER: Financiera de Desarrollo Territorial S.A. (In English: Territorial Development Finance).

FMAM: Fondo para el Medio Ambiente Mundial (In English: Fund for the Global Environment)

FMI: Fondo Monetario Internacional (In English: International Monetary Fund).

FNR: Fondo Nacional de Regalías (In English: National Royalty Fund)

FSSRI: Fondo De Solidaridad Para Subsidios y Redistribución de Ingreso (In English: Solidarity Fund for Subsidies and Income Redistribution).

FW: Food Waste

GEERED: Global Energy Efficiency and Renewable Energy Fund

GEF: Global Environment Facility

GIZ: German Society for International Cooperation

h: Hour

HM: Horse manure

IAF: Inter-American Foundation

IAPP: Industry-academia partnerships

IDB: Inter-American Development Bank

IFAD: International Fund for Agricultural Development

IFC: International Finance Corporation

IPSE: Planning and Promoting Energy Solutions in Non-Interconnected Zones.

JICA: Japan International Cooperation Agency

kg: Kilograms

KIW: German bank Kreditanstalt für Wiederaufbau

kW: Kilo Watts

LCA: Life Cycle Assessment

MARD: Ministry of Agriculture and Rural Development

MBW: Municipal biowastes

MESD: Ministry of Environment and Sustainable Development.

MME: Ministry of Mines and Energy

Mt: Megatons

NAMAS: Nationally Appropriate Mitigation Action

NCS: Non-centrifugal cane sugar

Nm^3: Normal cubic meters

OWW: Offal wastewater

PM: Pig Manure

PS: Primary sludge

PVC: Polyvinylchloride

PWS: Pig Waste Sludge

PWW: Paunch wastewater

RedBioCol: Red Colombiana de Energía de la Biomasa (In English: Colombian Biomass Energy Network).

RL: Ruminal Liquid

SCM: Sugarcane Molasses

SCS: Sugarcane Scum

SENA: Servicio Nacional de Aprendizaje (In English: National Learning Service)

SWW: Slaughter wastewater

SMA: Specific Methanogenic Activity

TJ: TeraJoules

UASB: Upflow Anaerobic Sludge Blanket

UNAL: Universidad Nacional de Colombia (In English: National University of Colombia)

UNDP: United Nations Development Program.

UNEP: United Nations Environment Program

UNIDO: United Nations Industrial Development Organization

UPME: Mining and Energy Planning Unit

USAID: United States Agency for International Development

VFA: Volatile fatty acids

VN: Vinasse

VS: Volatile Solids

ZNI: Non-Interconnected Zones

1. Introduction

Anaerobic digestion (AD) is a useful technology for waste management. This technology uses a substrate, which typically comprises animal manure, wastewater, or organic waste, transforming it into biogas and digested. Biogas is recovered as energy via cogeneration and used for cooking, electrical energy generation, or heating, while the digestate is used as a fertilizer. Due to the relevance of AD as a key technology for waste valorization, interest in its research and development has been gradually growing worldwide, thus allowing an improvement in the conditions and equipment required for AD, favouring its implementation [1].

At the world level, the situation, challenges, and perspectives of AD have been analyzed at the continental level (for example, Europe [2–6], Africa [7–9], India [10–12], China [13,14], Latin America [15], or focus on a general concept of developing countries [16,17]. In the case of Asia and Africa can be found some publications at a national level due mainly to the national biogas programs running [8,18]. In the case of Latin America, where technology development is characterized by the widespread of psychrophilic low-cost tubular digesters in the absence of long-term national biogas programs, exists a regional analysis publication [15].

In developing countries, AD technology has become crucial not only for waste valorization but also to meet the energy demand, especially remote, non-interconnected rural areas, thus enabling developing countries to supply cheap energy, and to improve the quality of life of rural inhabitants.

The implementation of AD in developing countries is primarily focuses on small-scale biodigesters, commonly known as household biodigesters. This type of installation has the advantages of a low volume (maximum 10 m^3) and size, low cost, easy handling, and maintenance. In developing countries, pig or cow manure is commonly used as a substrate, and the biogas is mainly used for cooking and electricity generation [19].

Colombia is a developing country in South America, where around 66% of the national territory does not have public electricity services through the National Interconnected System

[20]. The main sources of residual biomass are agricultural activities [21], livestock production, and the processing agro-industry. This residual biomass can support up to 15% to 28% of the end-use energy mix in the country [22]. In Colombia, AD has been adopted for the sustainable management and energy recovery of organic wastes and it is considered a clean and environment-friendly technology that can help rural communities meet their energy needs and, consequently, improve their living conditions [23]. Fixed domes, floating drums, and tubular digesters are the most common models implemented in developing countries [24]. Tubular digesters (or plug-flow reactors) are popular in Colombia owing to their low cost, the possibility of operation at various temperatures, and ease of implementation and handling [25,26]. Besides, these digesters do not require mixing to avoid material sedimentation inside the reactor or active heating to increase the temperature of the liquid. Passive solar heating designs have been used to adapt the tubular model to cold climate regions [27,28]. These observations indicate that AD technology is an opportunity to promote sustainable agriculture and improve living standards in rural areas.

Although the AD technology has been applied for a long time in developing countries, and that Latin America has its proper technology development through the widespread of tubular digesters, there is a lack of analisys to understand deeper the context, the history, barriers, and opportunities from the point of view of Latin American. To fill this gap, this study aimed to understand the current status and perspectives on anaerobic digestion sector from Colombian national level, as example of Latin America developing country. We analyze AD national context, and the technologies, regulations, and lessons learned in Colombia, in order to support the widespread application of AD technology to different sectors in developing countries.

The review is structured as follows: First, research on AD facts has been discussed. Second, under controlled conditions, wastes used as substrates for biogas production at the laboratory level were analyzed. Third, AD technology development in the household sector, including a nationwide analysis of the digesters by administrative regions (departments in Colombia), has been reviewed. Fourth, a review of Colombia’s regulatory entities and current legislation on renewable energy sources, including AD, is presented. Finally, barriers, lessons learned, challenges, and opportunities have been discussed to develop technology focusing on local farmers/rural populations.

2. AD facts in Colombia

The 1970s and the first half of the 1980s witnessed a rapid growth in the use of biogas, mainly in Asian, Latin American, and African countries [29]. Different enterprises —*government and non-governmental organizations*— promoted this growth that facilitated the installation, development, and technology diffusion, mostly in rural areas. Globally, China and India were the two largest household biogas users owing to their experience in technology and economic and technical support through public investment [15]. However, in Latin America, long-term financial subsidies were absent, and there was a lack of institutional support and follow-up. Therefore, the number of digesters installed in this region was considerably low [30,31]. Even though most installed digesters are found in Asia, remarkable research achievements have been reported from Latin America, contributing to increasing operational, technical, social, and environmental experiences [15,32].

In Colombia, the first design and installation manual for tubular digesters was published in 1987 [33]. Introduced, this model became the most widespread in Latin America. Since then, the Center for Research on Sustainable Agricultural Production Systems (CIPAV in its Spanish initials) has worked with farmers on AD research projects (largely with the tubular digester model) related to sustainable livestock, ecological restoration, and environmental services. The CIPAV edits and publishes the international peer-reviewed electronically and indexed journal Livestock Research for Rural Development (LRRD), an international peer-reviewed and indexed journal [34] to foster knowledge-sharing on topics covering sustainable rural development with a focus on AD [35].

Since the early 2000s, the Fundación Para la Producción Agropecuaria Tropical Sostenible, linked to The University of Tropical Agriculture Foundation, has played a pivotal role in AD promotion, installation, and research, with a focus on small and medium farmers, in Colombia. The foundation has been working on implementing digesters for more than 20 years, sharing experiences from Vietnam and Cambodia in South Asia, where it has worked on research, training, and rural development [36].

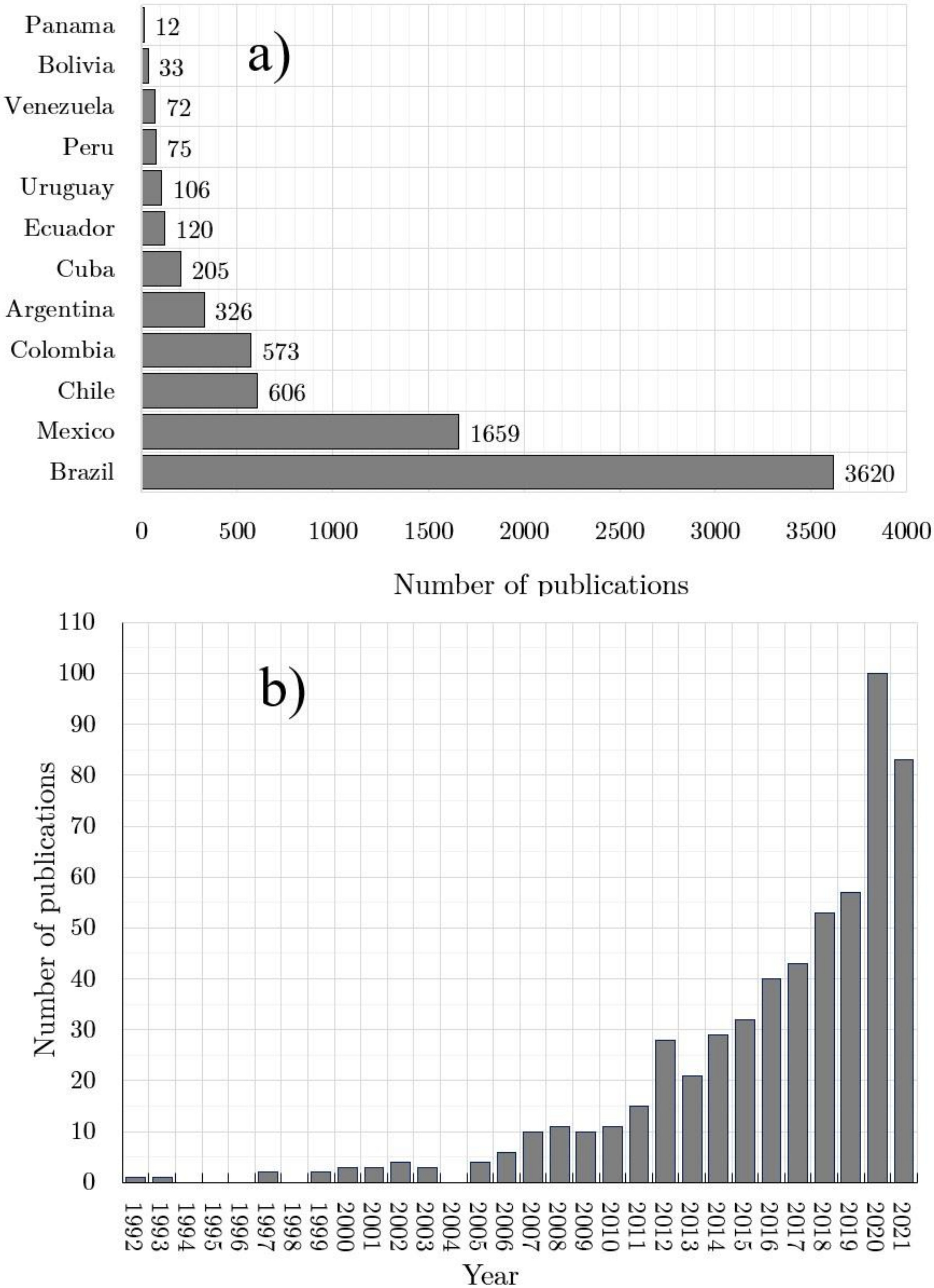
Considering household digesters as an alternative to promote the reduction of watershed pollution from livestock and agricultural exploitation, during the fourth conference on "Network of Biodigesters for Latin America and the Caribbean" (RedBiolac), it was proposed to engage in partnerships with the experiences of a Colombian Network [37]. As a result, in 2012, the Colombian Biomass Energy Network (RedBioCol) was founded. Currently, RedBioCol integrates experiences with different types of digesters at different scales, based on experiences from industry, small users, and academies. RedBioCol also focuses on strengthening AD technology by solving pollution-related problems, transforming waste into energy products, and promoting technology adoption by farmers [38].

Initially, AD technology in Colombia was implemented specifically for wastewater treatment. However, with the arrival of RedBioCol and its efforts to promote this technology, its use was expanded as an alternative for treating rural waste. In the last ten years, considering the advantages of AD, Colombian researchers have shown an interest in studying operating conditions and influencing variables that could allow the optimisation of this process.

Regarding the research on AD, scientific publications on biogas in Colombia have grown rapidly in the last decade. A systematic review of the existing publications on AD in Latin America and Colombia was conducted using the keyword search method in the Scopus database (keywords: co-digestion, anaerobic digestion, biogas, rural Figure 1-a shows). The Latin American countries with the largest number of publications from 1992 (the oldest publication) to 2022 are Brazil with a total of 3620 publications, followed by Mexico (1659), Chile (606), and Colombia with a total of 573 publications. Brazil has been the leader in anaerobic digestion in Latin America since the 19th century; the country has had a special interest in research and investment in alternative energy sources, including bioethanol and biodiesel. This interest has resulted in crucial participation of the federal government in terms of regulation, incentive programs for alternative energy sources, and market interventions, which favored the research and development of renewable technologies such as digestion.

Likewise, in Brazil, there is a high ability for private investment and entrepreneurship to support these types of projects, and a high experience in experimentation with biogas technologies that dates back from 1970 [39,40].

Figure 1-b shows the publications on AD per year by Colombian institutions or entities, with a total of 573 papers published to date. The first publication appeared in 1992, which presented the effects of mass transfer on the half-saturation constant for H_2 uptake kinetics [41]. However, between 1993 and 1997, there was a lacuna in research. Since 1997, there was an average of one publication per year until 2006, when the number of publications increased year by year, eventually reaching 82 in 2021. This growing trend is due firstly to the great potential of this technology that arouses a lot of interest in Colombian researchers, and secondly, to the initiative for the implementation and development of the technology that RedBioCol has driven. While reviewing Colombian research, it was noted that many of these were carried out in collaboration with universities or research centers in developed countries such as the United States, UK, France, Germany, and Spain.


a)
Panama
Bolivia
Venezuela
Peru
Uruguay
Ecuador
Cuba
Argentina
Colombia
Chile
Mexico
Brazil
12
33
72
75
106
120
205
326
573
606
1659
3620
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1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Year

Figure 1. Publications on AD from 1992 to 2021: a) Latin-American countries and b) Colombian publications by year.

The investigations on AD carried out in Colombia focused on studying the process using different feedstock (substrates and inoculums) from local agricultural and agro-industrial activities, configurations of digesters, and operating conditions. It is noteworthy that hundreds of low-cost digesters were already working on the farms [42], and the academia learned full-scale AD processes from the farmers, initiating a feedback process. This two-way knowledge transfer was carried out with the help of small and medium farmers, developing different methods, according to the biomass available in each area, in order to value them and offer a renewable energy alternative.

Additionally, other Colombian researchers have focused on full-scale household digesters to determine the parameters and performance of the process under real conditions [43–48]. Monitoring comprised taking frequent samples (influent, effluent, digestate, and biogas). These samples were characterized by measuring the biochemical methane potential (BMP), methane content, residual methane potential, specific methanogenic activity (SMA), organic matter content and consumption, volatile fatty acids, biogas production, methane concentration, and pH. These data were used to calculate energetic and economic potential with the implementation of the technology. Furthermore, the researchers proposed improvements to the process that increased the yield and quality of the biogas obtained and stabilized the effluent for agricultural reuse, thereby allowing a constant development of the technology on a small scale.

3. AD potential from Colombian waste

In the Colombian agricultural context, many residual biomass sources can be used as substrates. On average, Colombian organic waste production is approximately 117.5 Mt/year. From a global point of view, using these residues as an energy source can potentially produce 449,801.85 TJ/year [21].

Among the substrates studied, a wide variety of raw materials predominated and can be classified into three large groups: agricultural residues (benefit wastes and fruit wastes), domestic and industrial residues (food waste, cheese whey, or slaughterhouse wastewater), and livestock residues (pig, cattle, horse, and poultry), with their BMP ranging between 0.03 Nm^3 CH_4/kg VS and 0.78 Nm^3 CH_4/kg VS, which represents an energy contribution between 0.3 kWh/kg VS and 7.77 kWh/kg VS [49,50].

Table 1 displays a compilation of the experimental BMP data published in the literature. The search criteria were as follows: i) biomass (inoculum and substrate) from Colombia, ii) experimental conditions (inoculum/substrate ratio and mesophilic temperature range) [51], and iii) articles published since 2010. Before 2010, no BMP tests were reported in Colombia. We consulted the following databases: Scopus, Web of Science, Redalyc, and Science Direct. In addition, the information published in RedBioLac and Livestock Research for Rural Development journals was also considered. Based on these criteria, 29 papers were identified. Most experimental data were published from 2018 to 2022, indicating a keen interest in this research topic.

Studies have shown that the anaerobic co-digestion (AcoD) of mixtures with different substrates resulted in improved process performance, given a better balance in the composition of the mix that stimulates biogas and methane production [52]. Additionally, AcoD can improve internal conditions, such as pH or volatile fatty acid (VFA) content, representing a stable process without inhibition risks. The experimental data presented in Table 1 reveal an increase in mass yield, between 14% and 22%, in systems where the main substrate in AcoD consisted of sugarcane scum with agricultural crop residues [53] and chicken manure mixed with industrial wastes [54].

The Colombian studies revealed a variety of potential waste-as-resources used both as substrate and inoculum (after substrate stabilization) in AD or AcoD processes. The studies on these widely available biomass resources highlight the increasing interest in AD in Colombia and their potential energy, economic, and environmental impacts, which can be realized through bioprocesses.

AD comprises hydrolysis, acidogenesis, acetogenesis, and methanogenesis, carried out by a microbial consortium. The inoculum is an important factor in conducting a BMP test to determine the biogas potential of a substrate. A suitable inoculum can increase the degradation rate, enhance biogas production, shorten the starting time, and make the digestion process more stable [55]. Selecting an inoculum involves considering the origin, volatile solid content, and specific methanogenic activity. The literature reports two sources of microbial consortia (inoculum) for BMP assays: granular/floccular (9 papers) and different manures (16 articles). Owing to their high availability and promotion of their use by various entities such as RedBiolac and National Learning Service (SENA, by its initials in Spanish), manures generated in livestock activities are widely used as a source of inoculum.

Table 1. Summary of BMP of different sources of substrate and inoculum in Colombia.

Year	Reference	Substrate (s)	Inoculum	BMP* (Nm^3CH_4 /kg VS)	
				Mono-digestion	**Co-digestion**
2012	[56]	Fique bagasse	Ruminal liquid (RL) and pig waste sludge (PWS)	0.30	-
2014	[57]	Fique bagasse	Ruminal fluid (RF) and pig manure sludge (PMS) (Mixture 1:1)	0.35	-
2015	[58]	Chicken manure (CkM)	Cattle slurry	0.55	-
2016	[59]	Vinasse (VN) and CkM	Cattle slurry	-	0.65 (VN:CkM 3:1) 0.56 (VN:CkM 1:3)
2016a	[60]	Municipal biowaste from a university restaurant	From UASB reactors and an anaerobic sludge digester	0.07	-
2016b	[61]	Municipal biowastes (MBW) and selective collection with domestic wastewater sludge (DWS)	Obtained from an anaerobic digester of the municipal WWTP of DWS	0.104 (MBW) 0.073 (DWS)	0.106 (DWS:MBW 1:4)
2016	[62]	Sewage sludge primary sludge(PS) and food waste (FW)	Digested sludge	0.19 (PS) 0.20 (FW)	0.25 (PS:FW 1:2.3)
2016	[63]	Slaughterhouse wastewater	Cattle manure	0.73	-
2017	[64]	Pig manure (PM), municipal solid waste (MSW), and Cocoa industry residues (CIR)	Sludge from a biodigester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca.	0.44 (PM) ** 0.38 (MSW) ** 0.20 (CIR) **	
2018	[65]	Cheese whey	Cattle slurry	0.51 - 0.60	-
2018	[54]	Chicken manure (CkM), sugarcane molasses (SCM), and cheese whey (CW)	Cattle manure	0.34 (CkM)	0.57–0.66 (CkM:SCM:CW 1:1:1)
2018	[66]	Fruit waste: banana, dragon fruit, mango, goldenberry, and pineapple	Pig manure (PM)	0.35 (dragon fruit) ** 0.26 (mango) ** 0.24 (goldenberry) **	-

				0.23 (banana) ** 0.22 (pineapple) **	
2018	[67]	CIR, PM, organic fraction of municipal solid waste (MSW), and bottled beverage industry waste (BBIW)	Sludge from a digester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca.	0.48 (PM) ** 0.33 (MSW) ** 0.25 (CIR) ** 0.13 (BBIW) **	0.12–0.36 (mixing ratio not reported)
2018	[50]	CIR, PM, and coffee mucilage (CfM)	Sludge from a biodigester located at the sewage plant of Alpina S.A., in Sopo, Cundinamarca	0.45 (CfM) ** 0.78 (CIR) ** 0.53 (PM) **	-
2018	[68]	Food waste from the restaurant of the University of Valle	Sludge from a methanogenic reactor that treats cattle slaughter wastewater	0.15	-
2019	[69]	Bovine manure (BM), horse manure (HM), and PM	Diluted manures (BM, HM, and PM) were used as a source of inoculum	0.104 (BM) 0.170 (HM) 0.145 (PM)	0.19 (BM:PM 3.4:1) 0.47 (BM:HM 1:1.8) 0.42 (BM:HM:PM 6.5:1.5:1)
2019	[70]	Mango fruit waste	PM	0.75 **	-
2019	[71]	Fish waste	Anaerobic sludge from a UASB reactor treating wastewater from a slaughterhouse	0.47 (1% TS)	-
2019	[49]	Aged landfill waste	A mesophilic anaerobic digester treating municipal wastewater solids	0.035–0.038	-
2019	[72]	Wastewater (WW) from the Pontificia Bolivariana University and aerobic sludge from secondary treatment (AS)	Anaerobic sludge from a wastewater treatment plant of soft drinks	-	0.32 (WW:AS 1:60)
2019	[43]	Cattle manure	Cattle manure	0.69	-
2019	[71]	Grass from public green spaces of the tropical city of Palmira, Colombia	Mesophilic anaerobic sludge from a UASB reactor treating domestic wastewater from Ginebra, Colombia	0.33	-

2020	[73]	Gulupa (purple passion Fruit)	PM	0.41 (Gulupa peel) ** 0.31 (Gulupa pectin free) **	-
2020a	[74]	Sugarcane scum (SCS)	Cow manure digested sludge	0.23 (12.5% SCS Dilution)	-
2020b	[53]	Sugarcane scum (SCS) and agricultural crop residues (ACR) from the non-centrifugal cane sugar agribusiness sector	Cow manure digested sludge	0.21 (SCS) 0.26 (ACR)	0.28 (ACR:SCS 3:1)
2020	[75]	Municipal solid waste from a regional landfill in Valle del Cauca, Colombia	Granular sludge from an anaerobic digester receiving wastewater from a cattle and pig slaughterhouse in Valle del Cauca, Colombia	0.43	-
2021	[76]	Mixture of food waste (FW) / garden waste (GW)	Mixture of granular sludge:flocculant sludge	0.07 (FW) 0.08 (GW)	0.26 (FW:GW 1.7:1)
2021	[77]	Food waste (FW)	Mixture of granular sludge:flocculant sludge 75:25 v/v	0.09 (fresh) 0.135 (thermally pretreated)	-
2021	[78]	Slaughter wastewater (SWW), offal wastewater (OWW), and paunch wastewater (PWW) from a Colombian bovine slaughterhouse	Mesophilic cattle sludge	0.505 (SWW) 0.425 (OWW) 0.154 (PWW)	0.51 (SWW:OWW 2:1)

* BMP values were normalised to standard conditions (273.15 K and 100 kPa). Co-digestion ratio in VS.

** Does not report temperature and pressure conditions.

The main inoculum used in BMP tests is stabilized manure from cows (seven research studies) and pigs (three research studies) that serves as alkalinity or nitrogen source. The volatile solid content of the inoculum is a crucial factor because this variable is related to the content of active microbial biomass and determines whether dilution is required. Several papers have reported the contents of volatile solids ranging from 15 to 84.5 g SV/kg and 7.9 to 80.5 g/kg for granular/floccular and manure inoculums, respectively. SMA is a critical factor in AD that determines the methane-producing capability of the inoculum for a specific substrate at the concentration level, wherein substrate availability is not a limiting factor [79]. Unfortunately, this information was absent in most of the reviewed articles (69%). In the articles containing this information, the SMA reported ranged between 0.14–0.17 g COD/g VS for flocculent/granular and between 0.023–0.152 g COD/g VS for manure.

4. Development of AD technology

AD is carried out in biogas digester systems. These systems can be categorized into small-to medium-sized (5-20 m^3), and large-scale (>20 m^3) plants. The medium (a term not widely applied) and large-scale refer, generally, to plants implemented in industrialized zones with large amounts of substrate production (such as wastewater sludge from wastewater treatment plants or agricultural or industrial plants). In contrast the small-scale refers to domestic, household decentralized, farm, and communal biogas plants [80].

4.1 AD technology development at small and medium scale

The term household digester is extensively used to refer to small-scale biogas plants with low technological requirements, which are generally used in rural areas. AD application in household digesters offers numerous benefits, such as easy installation and operation, low cost, and size flexibility. The most well-known digester designs are fixed domes, floating drums, covered lagoons, and tubular digesters, which are considered the original Colombian technology.

In particular, at the end of the 1980s, the CIPAV introduced the tubular digester, also called the Taiwan type, in Colombia [81]. Small users have used this design as one of the main configurations for carrying out the AD process in rural areas [82]. This type of digester is generally cylindrical and is made of polyvinyl chloride, polyethylene (the same plastic used for greenhouses), or geomembrane. The digesters are semi-buried in a trench, leaving the biogas bell visible. In 2002, CIPAV researchers reported that the performance of the tubular digester does not depend on the use of polyethylene plastic or PVC geomembranes [83]. This design consists of a sealed bag connected at each end to an above-ground pipe, which enters through the pipeline, and the digestate exits at the other end and is deposited in a storage tank. A third pipe at the top of the cylindrical bag acts as the biogas outlet [84]. This household digester has a constant volume and operates at variable pressures to produce biogas [85].

Data on Colombian digesters installed and their characteristics were obtained via an online survey (using Google Forms) and oral communication (telephone interview). This survey was the first step in gathering information from RedBioCol partners, universities, foundations, and associations (n = 14 organizations) with experience with the AD process or digester installation. Additional information was also compiled from the websites of thirty-two regions in Colombia (known as departments). The keywords used were as follows: i) department name, ii) anaerobic digestion, iii) digester and iv) name of local environmental and governmental institutions. The obtained data are presented in Table 2. Information on 69% of the Colombian departments was received for this study, corresponding to 996 digesters currently installed. Reports published by the Colombian Environment Ministry indicated that approximately 5,700 digesters were established in the national territory [86]. Therefore, the data collected in this review correspond to a representative sample of the AD technology panorama in Colombia (confidence interval: 99%; margin of error: 4%).

The popularity of tubular household digesters has increased owing to their low cost, long shelf-life, simple design, and easy transportation. The tubular configuration of the digesters is 79%, and the remaining 21% corresponds to other models (batch and lagoon) and is without specifications.

The departments that stood out for the greatest number of digesters installed were Caldas, Cundinamarca, and Santander. Most of the digesters are low-cost tubular digesters because of the presence of organizations (such as RedBioCol and SENA) that cooperate with local rural communities, offering support and training on topics related to anaerobic digestion and digester installation. In contrast, some departments have a low or no number of installed digesters. Many of these territories are not electrically interconnected areas. In these territories, there is clearly an opportunity to take advantage of this technology by managing the organic waste generated through agricultural activities in each region.

The volume of digesters is highly variable, mainly due to the availability of organic wastes and the climate, with larger sizes in cold regions to increase the hydraulic retention time of the AD process. Another factor that determines the size of the digesters could be related to the budget available for installation.

Cow, horse, pig, buffalo, goat, and fish manures are the most important substrates used in Colombia, based on ~ 69% of the recorded digesters in this study. The remaining percentage of digesters use organic waste from other unspecified sources. Prior dilution of the substrates is required to ensure that the digester functions properly, avoiding clogging and scum formation on its surface and ensuring continuous flow operation. Previous studies on animal manure reported 1:3, 1:3, and 1:7 dilutions of manure:water ratio for bovine, porcine, and horse manure, respectively. These dilution ratios favored the methanogenic activity of the process [69].

Psychrophilic tubular digesters represent a simplified and successful technology in the country. Two examples of studies where this technology has been deeply analyzed in real conditions in Colombia are Castro et al. (2017) [44] and Jaime-Jaimes et al. (2021) [46]. In the first case, a 9.5m^3 total volume digester without stirring or heating devices, fed daily with cow manure and working at 23.5 ºC, produced biogas after 35 days from the start-up. The digester obtained a specific methane production (SMP) of 0.10 $Nm^3CH_4/kgSV$ [44]. More information from this digester is found in section 4.3.4. When compared to mesophilic results, full scale digester fed with cow manure from [44] obtain halved SMP results (0.10 $Nm^3CH_4/kgSV$) than that reported by [87] for similar substrate at BMP tests at 36.5ºC, equal to 0.202 Nm^3CH_4/kgSV. This can be explained by the low HRT of the psychrophilic digester (35d) and because the digester was just beginning it operation and the AD microorganism could not be enough adapted to the psychrophilic conditions, as can be seen in the next case.

The other case is a 103 m^3 operational volume digester, without mixing of active heating devices, that operates in a 17.7 ºC mean slurry temperature [46]. The digester was fed with the swine manure mixed with water to clean the stables. The influent was around 4.16 m^3/d and the HRT was 25 days. The OLR was 0.52 kgVS/$m^3_{digester}$·d, the estimated SMP was 0.40 Nm^3CH_4/kgSV. The keg's key aspect of this digester was that has been operating for more than eight years. More information from this digester is found in section 4.3.5. Microbiological analysis revealed that the microbiota was adapted to psychrophilic conditions, thereby increasing methanogenic archaea content while decreasing bacterial populations. In this case, mesophilic results from [87] for swine manure BMP test at 36.5ºC reports 0.322 Nm^3CH_4/kgVS, do not show better results respect an eight years old psychrophilic digester. Although the HRT is reduced for psychrophilic conditions (25d), the 8 years old adapted microorganism looks to be able to produce similar or greater amounts of biogas than mesophilic.

From a technological point of view, there are room for action to improve those results, for example adding a previous process of pretreatment. An effective pretreatment can facilitate the degradability of complex organic molecules to convert them into smaller compounds to be used as substrates in conventional AD [88]. Thermal pretreatment of manure fibers with NaoH [89], or alkaline microwaving pretreatment [90] demonstrate that biogas production is increased. But adding most sophistication to the system, increase the investment, maintenance and operational cost of the digester, making it less accessible to medium and small farmers. Also, heating or energy conservation are important for improving the suitability of AD in cold regions [91]. When biogas is not used to generate electricity, so no waste heat is able from a Combined Heat and Power System (CHP), the biogas could be used to heat the digester. But, in Norway (temperature ranges from 1 to 13 °C) a burner was installed to heat the substrates to 37°C, being necessary to consume 85 kWh of the 105 kWh of the total energy produced by biogas [92]. So, if there are no waste heat from a CHP, the heating of the digesters, without increasing its complexity and investment cost, can be using passive solar heating design [26,28, 93].

Finally, low-cost tubular digester sacrificed more efficiency by more technological accessibility to farmers, balancing the lack of sophistication, with higher reactor volumes and passive devices for heating and mixing.

Table 2. Household digesters installed in Colombia, classified by departments.

Department	Number of digesters	Volume (m^3)	Substrates	Temperature	Type
Antioquia	11	12	75% pig manure (PM) and 25% horse manure (HM)	N/R	Discontinuous tank
	5	40	Cow manure, HM, and PM	-	-
	2	12	Unspecified manure	16.7 °C	Tubular
	1	N/R	Organic waste	N/R	
	1	20	PM	~15 °C	Tubular
Arauca	50	N/R	Unspecified manure	N/R	Tubular
	1	40	PM	18–24 °C	Tubular
Atlántico	1	40	Organic waste	18–24 °C	Tubular
	2	8–30	PM	18–24 °C	Tubular
Bogotá	3	40	Cow manure	25 °C	Tubular
	3	25	Organic waste (Not specified)	37 °C	-
Boyacá	1	32	PM	25 °C	Tubular
	1	40	PM	~15 °C	Tubular
Caldas	1	72	Cow manure	23 °C	Continuous flow
	250	variable	Organic waste (Not specified)	N/R	Tubular
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	1	21.6	PM and coffee leachate	N/R	Tubular
	5	8–40	Cow manure and PM or trout manure	N/R	Tubular
Casanare	2	14–16	Cow manure and PM	18–24 °C	Tubular
Caquetá	1	0.200	Cow manure	25–30 °C	Discontinuous tank
Cauca	1	300	PM	N/R	
	20	-	PM	N/R	Tubular
	1	40	Cow manure	N/R	Tubular
	4	14–40	PM and cow manure	15–24 °C	Tubular
Córdoba	1	20	PM	18–24 °C	Tubular
Cundinamarca	1	6	Cow manure	18 °C	N/R
	1	N/R	Organic waste (not specified)	N/R	Continuous flow tubular
	60	10.16	PM with water from the washing of the facilities, horse, bovine, and goat manure, and even free human waste	19–32 °C	Tubular

	200	12–28	PM, cow manure, fish manure, HM, and coffee leachate, depending on where it is installed	18–32 °C	Tubular
	10	9.6	Cow manure and PM	-	Tubular
	4	10	Cow manure and PM	20 °C	-
	1	1	Cow manure and PM	30 °C	Discontinuous tank
	67	6–40	Cow manure and PM or trout manure	15–24 °C	Tubular
Guajira	1	40	Cow manure	18–24 °C	Tubular
Huila	1	22.5	PM	N/R	
	1	47	Cow manure	17–31 °C	Tubular
Meta	21	0.20 - 10.73	60.7% PM 33.3% cow manure 6% human faeces	N/R	87% Tubular 13% discontinuous tank
	1	6	Fish manure	N/R	Tank
	1	10	Cow manure	35 °C	-
	6	10–40	PM and cow manure	18–24 °C	Tubular
Nariño	2	10–47	PM	25 °C	Tubular
	1	8	Cow manure		Tubular
Norte de Santander	11	N/R	Organic waste (Not specified)	N/R	-
Quindío	5	8	Coffee mucilage (CfM), grey and black water, and PM	18	-
	1	40	Cow manure	~15 °C	Tubular
Risaralda	4	14–40	PM, cow manure, and HM	15–24 °C	Tubular
Santander	1	N/R	Cow manure	N/R	Tubular
	14	N/R	Organic waste (Not specified)	-	-
	115	6	PM	21±6	-
	6	8	PM and cow manure	25	-
	6	6; 8; 10; 100	Mix whey, HM, cow manure, and PM	15; 18; 23; 30	-
	5	8	CfM and manure (type not specified)	22	-
	3	8	PM	28	-
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	8	N/R	Organic waste (Not specified)	N/R	Tubular

	5	8–40	Cow manure and PM or buffalo manure	15–24 °C	Tubular
Tolima	10	N/R	-	-	-
	25	6	Cow manure and PM	20 °C	-
	1	N/R	Organic waste (Not specified)	N/R	Tubular
	1	40	Cow manure	N/R	Tubular
	2	6–30	Cow manure and PM	18–24 °C	Tubular
Valle del Cauca	1	40	PM	N/R	Tubular
	1	0.190	Organic waste (Not specified)	N/R	-
	1	20	Water- CfM	25 °C	-
	7	14–40	Cow and pig manure	15–24 °C	Tubular
Vichada	1	12	Fish manure	N/R	Tubular
	1	8	Organic waste (Not specified)	N/R	-
	1	12	PM	N/R	-
	1	20	Organic waste (Not specified)	N/R	Tubular
	5	8–20	Cow manure	18–24 °C	Tubular

Prior dilution of the substrates is required to ensure that the digester functions properly, avoiding clogging and scum formation on its surface and ensuring continuous flow operation. Previous studies on animal manure reported 1:3, 1:3, and 1:7 dilutions of manure:water ratio for bovine, porcine, and horse manure, respectively. These dilution ratios favored the methanogenic activity of the process [69].

Regarding the quality of biogas, in terms of methane content, it could be inferred from previous studies on tubular household digesters using different substrates that it remains above 40% and achieves an increase with temperature from psychrophilic conditions (40–65%) to mesophilic (60–70%) [15,25]. This makes it possible to cover the fuel needs for thermal energy, cooking and heating, mainly, and in some cases, to supply mechanical energy in engines of agricultural machines. Small-scale biodigesters (8-15 m^3) produce around 3 m^3/day and allow to meet the energy requirements in cooking food for 5-8 people. Medium-scale biodigesters (>40 m^3) deliver approximately 8 m^3/day, and biogas is used to sterilize milking machines and heat piglets. Besides, in the case of some small-scale biodigesters, H_2S is removed through a packed iron oxide biogas filter. However, on a medium scale, there is an obstacle to using biogas in other more specialized applications for which advanced desulfurization technologies [94] or low-cost natural materials [95] are required in the purification and upgrading of biogas. Since the technology has come out of the laboratory directly to rural areas, several risks have been identified, among them: CO_2 emissions, CH_4 and NH_3 explosion, high concentrations of H_2S cause negative effects on the water, it is very toxic irritant and can inhibit respiration [96]. However, all these risks are currently not considered.

4.2 Large-scale AD technology development

In Colombia, the beginning of the AD implementation on a large-scale date back to 1982, when the first large-scale digester for wastewater treatment was installed (Cañaveralejo Plant, Cali). After the success of the first pilot plant, two larger projects, financed by the

Dutch Cooperation, were established: the Vivero Plant by the Empresas Públicas Municipales de Cali (EMCALI) and the Rio Frío plant by the Environmental Authority Corporation for the Defense of the Bucaramanga (CDMB) [97].

Since then, AD has been implemented on a large-scale in both the public and private sectors for treating sewage or waste treatment generated in their production processes. Mainly two types of digester configurations have been used in the country: the Upflow Anaerobic Sludge Blanket (UASB) and the covered lagoon type digesters. The UASB reactor was developed in the 1970s in the Netherlands, and it is widely used worldwide, including in Colombia, on a large-scale owing to its technical and economic advantages, the possibility of treating granular sludge, excellent settling abilities, extremely low sludge volume, and improved separation [98]. The UASB reactor is used in wastewater treatment plants as an initial process and is the most technically and legally developed reactor in Colombia [99]. On the other hand, the covered lagoon is utilized for the treatment of animal manure. This system consists of a lagoon completely covered and hermetically sealed with a high-resistance PVC or polyethylene geomembrane. A covered lagoon operates at an ambient temperature without the requirement for heat [27]. Table 3 presents a large-scale review of the digesters installed in Colombia.

Table 3. Large-scale digesters installed in Colombia, classified by Department

Department	Company	Number of digesters	Volume (m^3)	Substrates	Type
Antioquia	Grupo EPM - PTAR Bello	6	-	Sludge	UASB
	Colanta	1	-	effluents from dairy production	UASB

Atlántico		1	2500	-	Covered lagoon
Bogotá	Doña Juana	-	-	Municipal organic waste	UASB
	Salitre	-	-	Sludge	UASB
Cauca	Palmar Santa Elena	1	500	Effluents from palm oil and biodiesel extraction	
	Palmeiras	1	7000	Effluents from palm oil and biodiesel extraction	
César	Indupalma	1	-	Effluents from palm oil and biodiesel extraction	-
Cundinamarca	Alpina	1		Effluents from dairy production	

Meta	Aceites Manuelita	2	19 000		-
	Palmeras del llano	1	750[3]	Effluents from palm oil and biodiesel extraction	-
Nariño	Palmar Santa Elena	1	500	Effluents from palm oil and biodiesel extraction	
		1	23 642	Cow and pig manure	Tubular
	Palmeiras	1	7000	Effluents from palm oil and biodiesel extraction	
Santander	Indupalma	1	16 000	Effluents from palm oil and biodiesel extraction	

	Bavaria	1	-	Effluents from brewing plant	UASB
	El Carrasco	1	60	Leachate from landfill of municipal wastes	UASB
	Río Frío Bucaramanga	1	6 600	Sludge	UASB
Tolima	-	1	1500	Pig manure	Covered lagoon
Valle del Cauca	PTAR Cañaveralejo EMCALI	4	-	Sludge	UASB
	PTAR El Vivero	1	1000	Sludge	UASB
	Bavaria Valle	1	-	Effluents from brewing plant	UASB
	Ingenio San Carlos	1	-	Effluents from the	-

sugar

industry

The large-scale implementation of AD in Colombia is represented by municipal wastewater treatment plants, as well as treatment plants for wastewater from palm oil, milk, and breweries. In some of these industries, the biogas produced is used to meet the energy needs of their production processes. However, in most cases, the percentage of gas use is only approximately 30%, while the other 70% is burned in torches to convert methane into CO_2 and expel it into the environment.

4.3 Case studies

4.3.1 El Común

El Común, a non-governmental organisation, is a pioneer in promoting biogas in Colombia. The contributions made by this organisation include installing productive units that donate two pigs to each rural family, installing a garage and a forage orchard, and installing and assembling a household digester (fig. 2). To finance these projects, El Común has the support of international entities such as Green Empowerment and Proyectos para un Futuro Mejor. According to the surveys carried out, El Común has installed 150 small-scale household digesters (6 m^3) until date, of which 115 are in operation, becoming one of the most successful cases in Colombia for the promotion and implementation of AD technology. Beneficiaries participate actively in installing the digester through community workdays and receive permanent training on various aspects such as animal feeding from forage, use of effluents, and technical management of the digester, among others.

Figure 2. Household digesters installed by El Común.
Image taken from the official website of El Común: www.elcomun.org

A similar case is ASPROINCA (Association of Indigenous and Farmers of Riosucio), which has installed more than 300 low-cost digesters. The association members can access plastic tubular digesters and are financed through revolving funds [31].

4.3.2 *Doña Juana*

A successful example of AD implementation on a large-scale and the use of biogas for electric power generation is the Doña Juana landfill in the city of Bogotá, one of the most important projects in Colombia. The project is structured in three plants, depending on the availability of connection points granted by the local energy network operator and approved by the UPME. Here, biogas is obtained from leached urban solid waste from the city of Bogotá and some neighbouring municipalities, and electrical energy is generated from the biogas obtained. With the implementation of this plant, it has been possible to achieve 35% compliance with the goals for Colombia agreed at the United Nations Conference on Climate Change 2015 (COP 21).

4.3.3. Experiences in Cumbal, alongside Ecuador border

Cumbal is a rural municipality with altitudes ranging from 1,000 to > 4,500 m and a mean ambient temperature ranging from 25–10 °C. In this municipality, the main population is indigenous, and the most common household activity is dairying and raising cattle and guinea pigs. Cumbal habitants are interested in solving the problems caused by cooking with firewood, such as deforestation and diseases, and exposure to smoke. An alternative to fulfil the energy requirements of Cumbal habitants is to carry out the AD process with the main residues generated: dairy wastewater, cattle, and guinea pig manure. With the support of the National University of Colombia, some research has been conducted to implement a household digester.

The low-cost tubular digester was arranged in a polyethylene cylindric bag (6.5 m length and 6 m^3 effective volume) covered with a greenhouse. Additionally, a reservoir was fitted to store 4.5 m^3 of biogas. The load was composed of a blend of 20 kg of manure (70% cattle; 30% guinea pig) and 60 L of dairy wastewater. This initiative provided important results; it was found that co-digestion of cattle and guinea pig manure and dairy wastewater increased the biogas yield 2.56 times compared with that obtained with cattle manure mono-digestion. The biogas produced was approximately 0.9 m^3/d with a quality of approximately 61% CH_4–69% CH_4. However, researchers have shown some operational problems owing to a lack of users. Thus, it was concluded that the correct operation of the digesters depends, to a large extent, on the commitment to system management.

***4.3.4** Marcella Farm: a family experience*

A traditional Colombian peasant family that used firewood for cooking installed a low-cost tubular digester built with tubular polyethylene, with an effective length of 7.5 m and a total digester volume of 9.5 m^3. The substrate was a mixture of bovine manure and rainwater in a 1:3 ratio. The manure was generated from three cows that were housed 65% of the day. The daily treated manure was around 51 kg, representing an organic load of 0.7 kg VS/$m^3_{digester}$*d (hydraulic retention time of 35 d). Owing to the installation of this digester, 0.85 Nm^3 biogas/d was generated (with 65.6% of CH_4) and used for cooking. In this way, the users generated enough energy to cook food for five people, saving 50 USD per month. Additionally, the digestate (around 0.14 m^3/d) presented high nutrient content, which was used for land spread [44].

4.3.5. "La Loma" farm digester. Pig manure treatment

La Loma farm is in the Boyacá department (altitude of 2,963 m and latitude of N 6 °27'45.0" W 72 °24'43.0"). This farm is located near the El Cocuy National Natural Park, and the average zone temperature is approximately 12 °C. Since 2012, the "La Loma" farm has focused its livestock activities on improving its residues disposition. In this context, it was decided to implement a pig manure anaerobic digester. A 30 m polyethylene anaerobic digester (103.1 m^3 operational volume) was covered with a polyethylene greenhouse for environmental protection and to improve internal temperature conditions.

The digester treats the manure produced by 255 animals at a 1:6 ratio mixture of dung and free-range wash water. The blend corresponds to a flux around 4.16 m^3/d (HRT = 25 days). In particular, the digester has been operating for more than eight years. In 2021, Jaimes-Estévez *et al.* [46] monitored this digester for five weeks to determine the performance of a psychrophilic rural digester. In this study, we assessed the thermal performance and microbiological and biochemical status of the digester. As a result of this experience, researchers found that greenhouse protection does not improve the internal temperature, and an alternative to trench insulation should be used. Microbiological analysis revealed that the microbiota adapted to psychrophilic conditions, thereby leading to an increase in methanogenic archaea content while decreasing bacterial populations. This adaptation resulted in an increase in hydrolytic and fermentative processes. The acclimatization and adaptation of the microorganisms allowed good digester performance to reach a high methane production of approximately 0.40 Nm^3CH_4/kg VS.

5. Colombian legislation and policies for biogas use

5.1. *Regulatory entities*

In Colombia, the Ministry of Mines and Energy (MME) and the Ministry of Environment and Sustainable Development (MESD) are the main governmental institutions that standardize and regulate public policies regarding the generation and use of energy and environmental care. The MME is supported by various governmental agencies, such as the Mining Energy Planning Unit (UPME) and the Institute of Planning and Promoting Energy Solutions in Non-Interconnected Zones (IPSE), which are in charge of capacity planning and support of policymaking, and the Energy and Gas Regulation Commission (CREG), which regulates power and gas tariff s.

The MME and MESD consider biogas as a non-conventional energy source and an alternative for mitigating climate change. On the other hand, the IPSE considers biogas as an alternative and energy solution for rural areas with no electricity supply, representing approximately 60% of Colombian territory. Therefore, the IPSE promotes and implements projects in the most remote areas of Colombia for the use of biogas technology in kitchens as a replacement for firewood and electricity generation. The broad reasons allow us to support this decision. This highlights that the production of biogas from different biomasses is an economically sustainable alternative that helps mitigate climate change and improve the quality of life of the communities. These projects also contribute to the income of the productive chains and promote caring for the environment through energy use from waste.

In Colombia, biogas production from solid waste in landfills began in the mid-80s. However, biogas generation from waste is unregulated in terms of production, transport, commercialization, and distribution. In 2009, the CREG published the first regulation applicable to biogas [100]. It established a “supervised freedom” figure for public service companies for biogas management through isolated networks only and exclusively for industrial users. This regulation prohibited the commercialization of biogas for residential users and the mixing of natural gas or liquefied petroleum gas with biogas.

The timeline of biogas regulations in Colombia is presented in Table 3. Since 2009, regulatory entities collaborating with the Colombian government began to combine efforts to improve regulations as needed. Consequently, some resolutions were issued by the CREG in 2012 [101,102]. Finally, in 2014, the Colombian government established a legal framework (Law No. 1715,2014) and tax instruments to promote non-conventional energy sources [88].

Table 3. Timeline of biogas regulations in Colombia.

Year	Law
2009	***Resolution CREG-056.*** This was the first regulation applicable to biogas. This regulation gives public service companies a figure of "supervised freedom" for distributing and commercializing biogas through isolated grids, only and exclusively for industrial users.
2012	***Resolution CREG-135:*** Regulation applicable to the domiciliary public services of fuel gas with biogas adopted.
	Resolution CREG-079: Regulation applicable to domestic public service of fuel gas with biogas produced by decomposition wastes.
2014	***Law 1715:*** Legal framework and the tax instruments for promoting, implementing, and developing non-conventional energy sources.
2015	***Decree 1077:*** Requirements for the viability of biogas as an energy recovery alternative and the need to monitor biogas composition.
2016	***Resolution CREG-240:*** This resolution repeals Resolution CREG 135 of 2012. The minimum quality requirements and safety conditions were established for the biogas and biomethane used in the domestic public service.
2017	***Decree 1784:*** Establishes in more detail the final disposal of solid waste, its management in landfills, and the requirements for its energy use, including the use of biogas produced.

In 2015, Decree-Law No. 1077 [103] was established, showing more details about the final disposal of solid waste and the requirements for its use as raw material to produce energy, including biogas. It is worth noting that there were no significant changes in the use and monitoring of biogas compared to those in the previous decree.

In response to the lack of regulations related to quality and safety of biogas commercialization, especially for domestic use, in 2016, the CREG established Resolution No. 240 [104], in which the standards applicable to domestic public service of fuel gas, including biogas and biomethane, were adopted. One of the main provisions established by this resolution is related to biogas quality and its monitoring (calorific value, Wobbe index, methane concentration, hydrogen sulfide, and carbon dioxide, among others).

5.3. Financing mechanisms and incentives

In Colombia, although the monetary funds for financing alternative energy projects are still somewhat limited, public funds are sponsored by the state and funds from international agencies. The first fund was created in 2014 through Law No. 1725, which establishes the Non-Conventional Energies and Efficient Energy Management Fund (FENOGE), financed by public or private national organizations and multilateral or international funding organizations. In addition, tax reductions and incentives are created for those organizations that invest in the research and development (R&D) of unconventional energy sources.

Regarding the promotion of research, this law dictates some provisions that promote research, technological developments, and innovation in non-conventional energy sources and their subsequent applications and adoption in the national energy system. To manage this initiative, the national government empowers regional autonomous corporations and local offices to include in regional development plans, measures that promote scientific research on alternative energy sources, which must be framed in national and global energy policies.

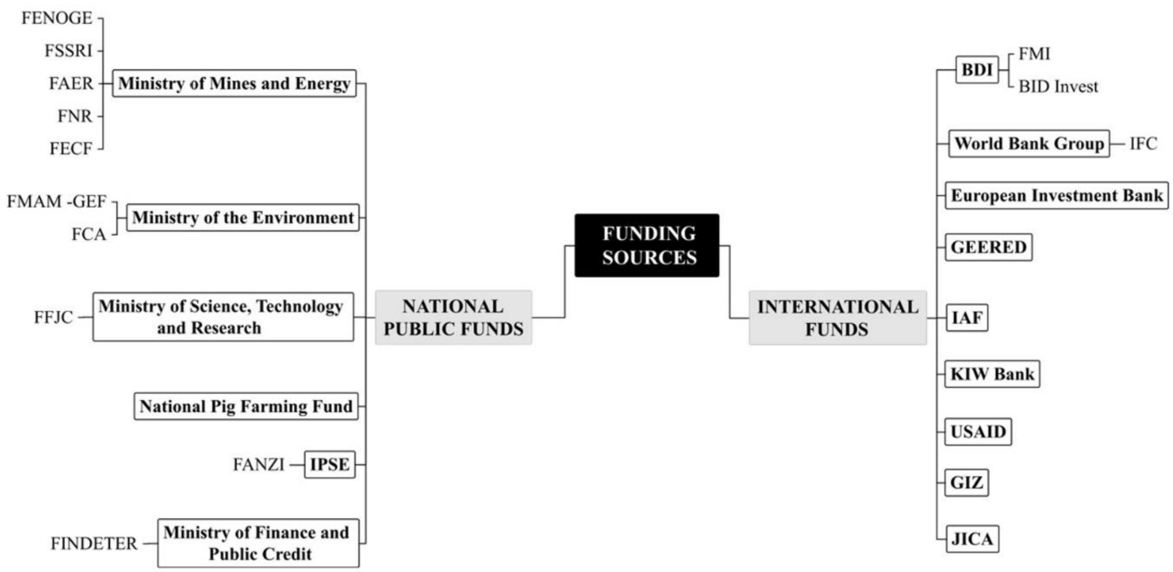

Figure 3. Funding in Colombia for the implementation of projects for the use of biogas.

The incentives, support programs, and reduction in taxes offered by the national government in this law have prompted some public and private companies to shift their interest toward the utilization of non-conventional energy uses, within which the use of biogas is generating great interest.

The Global Environment Facility (GEF), created in 1991 by the governments of 182 countries, international institutions, non-governmental organizations (NGOs), and the private sector, is the largest financial resource for projects to improve the global environment. Ten agencies comprise the United Nations Development Program (UNDP), United Nations Environment Program (UNEP), World Bank, Food and Agriculture Organization of the United Nations (FAO), United Nations Industrial Development Organization (UNIDO), African Development Bank (AfDB), Asian Development Bank (ADB), European Bank for Reconstruction and Development (EBRD), Inter-American Development Bank (IDB), and International Fund for Agricultural Development (IFAD).

In Colombia, financing investment plans, programs, and projects in energy infrastructure in non-interconnected areas (ZNI) are supported by the Financial Support Fund for the Energization of Non-Interconnected Zones (FANZI). This fund system was created by Law

No. 633 of 2000 [91] and regulated through Regulatory Decree No. 1124 of 2008 [105]. Currently, it is managed by the Ministry of Mines and Energy through the IPSE.

The research investments are focused on the National Fund for the Financing of Science, Technology, and Innovation Francisco José de Caldas (FFJC). FFJC is a financial mechanism that allows the Ministry of Science, Technology, and Innovation to finance the development of different science, technology, and innovation projects, among which can be highlighted the implementation of unconventional energy sources. Likewise, other public national funds exist to finance the projects aimed at implementing energy generation from unconventional sources that are managed by different national ministries. It is worth noting that there is a specific national agency for biogas production through pig manure, named the National Pig Farming Fund, which provides technical advice and finances projects related to this topic.

It should be noted that RedBioCol brings different actors in Colombia to promote the development of alternative energy and channelize resources from diverse public and private funds to implement AD as a technology for energy generation from organic waste.

Different international agencies are currently participating in financing renewable energy projects in Colombia. These entities are mainly the International Development Bank (BDI), World Bank Group, European Investment Bank (EIB), German bank Kreditanstalt für Wiederaufbau (KIW), the German Society for International Cooperation (GIZ), the United States Agency for International Development (USAID), Inter-American Foundation (IAF), Global Energy Efficiency and Renewable Energy Fund (GEEREF), Japan International Cooperation Agency (JICA), and Green Empowerment.

Finally, in Colombia, there are some credit programs to help establish low-cost digesters in rural areas. These programs are focused on farmers and are proposed by mixed banks such as FINDETER, the Fund for the Financing of the Agricultural Sector (FINAGRO), and private banking entities.

5.4. Environmental criteria and regulations

It has been estimated that biogas technology could potentially reduce emissions of methane (by 4%) and nitrous oxide, thereby mitigating global warming [20].

The MESD has implemented the Nationally Appropriate Mitigation Action (NAMAS) and sustainable development goals promoted by the United Nations. The implementation of biogas production is encouraged in different national policies, such as the National Policy for the Comprehensive Management of Solid Waste, CONPES No. 3874 of 2016 [106], which aims to implement waste management strategies that contribute to climate change mitigation and the promotion of a circular economy. Biogas production in sanitary landfills has been established as an alternative to valorization of urban solid waste. This strategy is also planned in the National Climate Change Policy [107], which presents opportunities to link the economy and climate change. It shows different strategies for rural, urban, mining energy, infrastructure development, and ecosystem conservation. Another policy aimed at this objective is the Green Growth policy [108], which establishes productivity and economic competitiveness objectives for 2030 in conjunction with the sustainable use of natural resources, climate protection, and social inclusion. Green growth promoted by this policy directly impacts the national objectives of building sustainable cities and communities, responsible production and consumption and achieving affordable and non-polluting energy sources framed within the functions of the IPSE.

These current policies are part of the 2014–2018 development plan. Three main objectives have been established: sustainable low-carbon growth, protection and assurance of natural capital, and vulnerability reduction to the risk of disasters and climate change. Likewise, this plan was adopted in 2015 by Law No. 1753 [109].

The Ministry of the Environment and the National Pig Farming Fund, Pork, Colombia, promotes the implementation of digesters for biogas production as a renewable energy alternative mainly for thermal use in rural areas, especially in non-interconnected areas. In addition, they created the Biogas Guide for the pork sector in Colombia, which proposes for small and medium producers to develop a sustainable pork production chain through the implementation of these energy alternatives. This guide contains technical and economic details for implementing these technologies, as well as financial and tax incentives that can be accessed, becoming a document of great support for the producer at different scales to seek sustainable production [86].

The development of alternative energy sources also involves certain environmental aspects, which are considered in Law No. 1715 [110]. Regarding this issue, the Environment and Development Ministry, National Environmental Licensing Authority (ANLA) and regional autonomous corporations have been assigned the task to formulate the guidelines and procedures that allow the evaluation and follow-up of possible environmental and energy impacts that may occur with the use of these new energy sources. Furthermore, the government is committed to developing new rules and regulations for emissions and discharges resulting from the use of these new energy alternatives. Unfortunately, policies for the implementation of low-cost digesters do not exist. Therefore, there are no regulations for low-cost digesters, and no licenses are issued for this type of project.

6. Barriers, opportunities, and challenges

Despite AD development in Colombia, some barriers limit the promotion and implementation of this technology in the country. The main limitations are as follows: obtaining resources to cover investment costs, lack of experience with biogas projects by the funders, perspective of the digestate market (uncertainty regarding the quality, use, and commercialization of the digestate in the country), and lack of regulation for the integration of biogas to electricity or natural gas networks. A significant barrier is the lack of understanding of the benefits and viability of this technology among the population, stakeholders, and even academia.

In developing countries such as Colombia, AD and biogas regulations are generally transferred from developed countries with other industrial and technological realities, more than a local response to local reality. In rural areas, where biogas plants have been installed for decades, and there is room for improvement, there is no government policy to reinforce this decentralized, small-scale, renewable energy technology as low-cost tubular digesters.

Currently, there is a disarticulation among academia, government, industry, and the communities. Although progress has been made in research at the laboratory level, it has not been easy to translate research progress into real-life applications despite favorable experiences. The lack of funding resources also strongly influences this aspect. Implementing AD on a large-scale is expensive, and it is difficult to highlight its advantages over other renewable energy sources for electricity production, as seen in Europe [2]. Nevertheless, biogas plants have an opportunity if they are linked with additional benefits that renewable energy technologies do not offer, such as waste treatment services and nutrient recycling for agriculture.

The AD R&D of organic residues in Colombia has mainly covered laboratory-scale studies, and small-scale digesters are typically used to produce biogas for heating and cooking purposes (see Table 3). Commercial digesters are used for electricity production to a lesser extent. Several studies have demonstrated the advancement of AD technology in Colombia and revealed the opportunities and challenges in the next few years [21]. In Colombia, the Ministry of Agriculture and Rural Development (MARD) divides the productive sectors into chains, among which the agricultural sector accounts for 7% of the country's GDP [98]. Different sectors have their demands regarding the management and use of waste and by-products generated [99]; hence, the government is looking for solutions to these problems.

The integration of AD in sustainable agriculture is a topic of interest from different points of view in Colombia. From an energy point of view, Preston and Rodriguez [111] estimated the energy return on energy investment (EROEI) of an integrated medium-scale farm that combines sugar cane and pig production with gasification and anaerobic digestion for energy production from organic wastes. The results revealed an EROEI of 8:1 ratio, indicating that eight energy units are obtained per energy unit introduced in the system (considering the energy associated with human labor and animal feed purchase), which is a good alternative to conventional biofuel production. An early publication by Chará *et al.* [112] in 1999, commented before, is also linked to the performance of a full-scale tubular digester in an integrated system for farm wastewater treatment. In 2009 [113] and 2011 [114], Rodriguez *et al.* published results comparing anaerobic digestion effluent from a low-cost tubular digester and biochar derived from gasification of sugarcane bagasse and native microorganisms collected from the same farm. The findings showed that the combination of biochar and AD effluent positively affected green biomass growth even better in soils without organic matter. The incorporation of native microorganisms improved these results. These results indicate the potential of using AD effluent mixed with biochar for increasing soil fertility and soil restoration. Therefore, sustainable agriculture in integrated farms can take advantage of energy and nutrient recovery while treating agricultural waste through low-cost digesters.

Colombia is one of the largest vegetable oil producers of palm oil worldwide. Currently, the planted area of palm oil exceeds 500 thousand hectares in the national territory [115]. Arrieta *et al.* [116] demonstrated huge potential for increasing the power efficiency of palm oil mills by generating biogas from the anaerobic treatment of wastewater and its conversion into electricity using CHP systems. The use of palm oil mill effluents in biogas production is an alternative that positively impacts all biorefinery concepts [117]. However, Ramirez *et al.* [118] argued that few mills carry out biogas capture, and only some generate electricity from biogas. Therefore, there is a possibility of technology transfer and optimization of the palm oil sector should be considered.

Rice production is also of great importance for the country since the crop occupies 350 thousand hectares, and its entirety is for internal consumption [119]. The AD of rice straw was tested as an alternative for treating this sub-product of paddy rice harvest to mitigate the environmental impacts caused by the illegal burning of rice straw in rural fields [120]. The effect of the inoculum/substrate ratio (I/S) on the AD of rice straw carried out in batch reactors at room temperature (25–27 °C) was studied. The results demonstrated a high biogas production (410 L/kg VS) at an 0.8 I/S ratio, with a methane content of over 70%. Furthermore, it was shown that using a natural microbial consortium as rumen fluid for lignocellulosic material degradation could be an effective and promising option. However, the study was conducted at the laboratory level; therefore, it is necessary to develop a model that involves scaling the technology.

AD integration models have been developed for various productive sectors. Non-centrifugal cane sugar (NCS) is one of the main products of Colombia since it stands out as the second-largest producer in the world after India, with 1.3 Mt of NCS production per year [121]. Mendieta *et al.* [122] developed a theoretical model for managing waste from the NCS agro-industrial sector. Similarly, Escalante *et al.* [65] developed a model for the dairy sector, including the production of biogas and struvite in the integration of AD technology. The next stage should consider validating these models in a real environment.

Ortiz *et al.* [123] studied the sustainable management of peel residues in small-scale orange juice industries. The life cycle assessment (LCA) established that anaerobic digestion with the recovery of the digestate for reuse in the cultivation of oranges is an environment-friendly option. However, higher costs are incurred than in the scenario where waste is incinerated. At this point, low-cost AD technology for the industry should be tested. Garfi *et al.* [48] assessed the environmental benefits of implementing low-cost digesters in small-scale farms in Colombia using the LCA methodology. Results showed that the implementation of digesters reduced considerably (by up to 80%) the potential environmental impacts associated with manure handling, fuel, and fertilizer use in small-scale Colombian farms, due to the reduction of liquefied petroleum gas and synthetic fertilizer use, which were replaced by biogas and the digestate. Similar benefits were observed with a low-cost digester using cattle manure as a substrate for use in rural areas for biogas production, with improved digestate quality [44].

In contrast, Mendieta *et al*. [124] evaluated the environmental benefits of implementing low-cost digesters to valorize agro-industrial waste in the non-centrifugal sugarcane sugar sector. The environmental impact of freshwater eutrophication and marine eutrophication showed a reduction of 87.6% and 99.4%, respectively, compared to the current scenario. Thus, by treating organic waste and wastewater on-site while producing bioproducts (*i.e.*, biofuel and biofertilizer), low-cost digesters could boost the circular bioeconomy in the NCS production sector.

Colombia offers a wide diversity of agricultural and livestock products because of its location in the tropical zone of the world. Consequently, a large amount of organic waste is generated throughout the year. On the other hand, Colombia has government support (MARD, MME, MESD) and human resources (universities, entities that provide agricultural technical assistance services, among others) to develop research projects focused on the mitigation of the environmental impact due to the generation of such wastes. Accordingly, some of the resources have been allocated to the promotion of anaerobic digestion technology.

There are several challenges that future research on AD in Colombia should focus on better understanding the reality of farmers and rural areas to link the investigation to the real-life necessities. Research must go hand in hand with the pillars of sustainability, which poses a dilemma with the agro-industrial sector, such as palm oil. At the social level, technology transfer can be expanded to achieve greater adoption of technology. Agricultural sectors remain unaware of anaerobic digestion or do not recognize the benefits of technology, which is why a mass adoption strategy is required. Regarding the environmental pillar, it is essential to investigate the benefits of anaerobic digestion for a certain sector, considering the current management of residual biomass and climatic conditions. The latter is important for the design and implementation of digesters. Finally, from the economic component perspective, it is necessary to adapt low-cost digesters to the conditions of each sector. Despite advances in R&D, policies are needed in Colombia to regulate the biogas chain, including production, transportation, commercialization, distribution, and its use, which would help AD position itself as a technology for energy production for the country.

7. Discussion and lessons learned

Anaerobic digestion technology has been promoted in recent decades, depending on the economic status of the regions. In developed countries, AD technology is positioned on an industrial scale to generate electricity for the grid through biogas combustion and is currently used for the production of biomethane [2]. However, in impoverished countries, small and medium-scale technologies are widespread and integrated into farms to use the biogas for thermal and cooking energy sources, wastewater treatment, and nutrient recycling. An example of this can be found in Latin America, [15] Africa [8], and for India [11]. Finally, most low-cost digesters in developing countries are installed on household farms, where the integrated agricultural system is working (combination of livestock and crops).

Evidence shows that most digesters installed in Colombia are unheated systems, similar to those in many other developing countries [7,15,125]. For instance, UASB for urban wastewater treatment, lagoon for large agricultural waste generator industries (palm oil or pig slots), and low-cost tubular digesters for medium and small farmers.

These have main effects on regulations and research. In terms of regulations, developing countries tend to implement rules adapted from developed countries with industrial AD, neglecting the local small and medium AD technologies being implemented without appropriate and adapted regulations. In the case of Colombia, regulations are focused on the distribution of biogas in an insulated grid, biogas composition, and safety conditions for biogas distribution. Those are more related to developed countries' needs and biogas sector development [2] than to Colombia's reality, while most of the digesters in the country produce biogas for in situ consumption, usually as cooking fuel.

From a research perspective, most digesters implemented in developing countries work at psychrophilic temperatures [2,15,125]. Furthermore, the methodologies (such as the BMP test [126]) and knowledge focus on mesophilic conditions according to the needs of developed countries that use to heat digesters. Therefore, there is a lack of research on psychrophilic AD that the impoverished countries have to cover, despite a lack of funding research.

Biogas technology suppliers in Colombia have limited capacity to transfer laboratory research to full-scale systems, unlike the biogas sector in developed countries. Academic researchers have covered this gap by focusing their studies on the performance of full-scale digesters. In addition, most methodologies and protocols in AD are for mesophilic conditions (heated digesters). However, the real-life setup in developing countries includes psychrophilic conditions (unheated, low-cost digesters). Hence, in this context, research on low-cost digesters has overcome the lack of proper laboratory-recognized psychrophilic methodologies.

The experience in Colombia is that low-cost AD biogas technology became widespread slowly but continuously, even without proper regulations or direct government support beyond recommendations or limited experiences. National and international NGOs promote this process, and local organizations such as RedBiocol drive the share of experiences and spread low-cost digesters in the country. As the universities have joined the RedBiocol and the research has been scaled-up, low-cost digesters is beginning to cover the gap in knowledge of long-term psychrophilic AD.

8. Conclusions

The main objective of this review was analyzing the current state of anaerobic technology, barriers, and opportunities in developing countries such as Colombia. Research and development on AD have been evolving in recent years, highlighting the interest of academia and industrial sector and increasing the implementation of this technology. Although AD technology has been in use since many years, there are still significant gaps in knowledge about its implementation and performance under long term psychrophilic conditions in rural areas, where the technology was initially developed through trial and error.

Research has focused on studying AD performance, using diverse substrates and local inoculum at the laboratory level to promote the sustainability of different agricultural sectors. The review carried out in this study found that manure from various livestock farms (mainly cow, horse, pig, buffalo, goat, and fish manure) is the most important substrate used in Colombia (69%), followed by organic wastes from other unspecified sources (31%). The main characteristics of the inoculum are its origin, VS content, and SMA. The main sources of inoculum used are stabilized cow manure and pigs.

Reports published by the Colombian Environment Ministry indicate that currently, there are approximately 5,700 digesters installed in the country. The departments with the highest number of digesters are Caldas, Cundinamarca, and Santander. The most commonly used type of digester in Colombia is the low-cost tubular configuration (79%). The remaining 21% correspond to other models (batch and lagoon) and are not specified.

Even though anaerobic digestion is considered a promising technology in Colombia, the AD sector faces critical challenges, such as feedstock pre-treatment using low-cost technologies, developing a sustainable market for biogas and digestate, and process safety in small and medium digesters. As well, the development of policies for renewable energy sources has been identified, and it is necessary to structure policies focused on AD to implement the technology throughout the country.

Finally, academic research is approaching the study of full-scale psychrophilic digesters, the vast majority of installed digesters in Colombia, as in the rest of developing countries.

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Highlights:

- Half of the Colombian AD publications are from the last three years.
- 79% of the digesters are low-cost and run under psychrophilic conditions.
- Mesophilic AD research on substrates, co-digestion, and inoculum dominates.
- There is a lack of regulation, support, and psychrophilic AD research.
- Multidisciplinary networks drive the spread and research of low-cost digesters.

RSER Author Checklist Table

Item	**Check**	**Important notes for Authors/Requirement**
Article type	Select the single correct article type here and state in brackets the paper word count. • Review article (8500)	Papers will be indexed as Full-length articles, Review articles, Retractions, Corrigendum, Addendum or Editorials as explained above in this GFA.
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