energies

MDPI

Review

An Overview of the Socio-Economic, Technological, and Environmental Opportunities and Challenges for Renewable Energy Generation from Residual Biomass: A Case Study of Biogas Production in Colombia

Lisandra Rocha-Meneses [1,*,†], Mario Luna-delRisco [2,*,†], Carlos Arrieta González [2], Sebastián Villegas Moncada [2], Andrés Moreno [3], Jorge Sierra-Del Rio [4] and Luis E. Castillo-Meza [5]

1 Renewable and Sustainable Energy Research Center, Technology Innovation Institute (TII), Masdar City, Abu Dhabi P.O. Box 9639, United Arab Emirates
2 Programa de Ingeniería en Energía, Grupo de Investigación en Energía—GRINEN, Universidad de Medellin, Medellín 050034, Colombia; carrieta@udemedellin.edu.co (C.A.G.); svillegas@udemedellin.edu.co (S.V.M.)
3 Grupo de Química de Recursos Energéticos y Medio Ambiente QUIREMA, Instituto de Química, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia, Medellín 050010, Colombia; jorge.moreno@udea.edu.co
4 Department of Mechatronics Engineering-MATyER, Instituto Tecnológico Metropolitano, Medellín 050536, Colombia; jorgesierra@itm.edu.co
5 Department of Environmental Engineering, Universidad Pontificia Bolivariana—Seccional Bucaramanga, Bucaramanga 680002, Colombia; luis.castillo@upb.edu.co
* Correspondence: lisandra.meneses@tii.ae (L.R.M.); mluna@udemedellin.edu.co (M.L.-d.)
† These authors contributed equally to this work.

Citation: Rocha-Meneses, L.; Luna-delRisco, M.; González, C.A.; Moncada, S.V.; Moreno, A.; Sierra-Del Rio, J.; Castillo-Meza, L.E. An Overview of the Socio-Economic, Technological, and Environmental Opportunities and Challenges for Renewable Energy Generation from Residual Biomass: A Case Study of Biogas Production in Colombia. *Energies* **2023**, *16*, 5901. https://doi.org/10.3390/en16165901

Academic Editor: Alan Brent

Received: 18 June 2023
Revised: 11 July 2023
Accepted: 13 July 2023
Published: 9 August 2023

Abstract: The escalating global energy demand, driven by heavy reliance on fossil fuels, worsens environmental degradation and triggers socio-economic shifts in extraction and refinery hubs. In Colombia, the energy matrix is predominantly fossil-based (76%), with hydroelectric power accounting for 70% of electricity generation. However, renewable energy sources only contribute 2% to the national energy mix. To reduce emissions by 20% by 2030, Colombia has presented an energy transition roadmap. The need for bioenergy production in Colombia arises from the residual biomass availability, the potential to provide sustainable energy access, and the potential to mitigate climate change impacts, while addressing energy poverty and enhancing energy security. This study presents an overview of biogas production in Colombia, emphasizing the need for financial resources to overcome barriers. Policy incentives, awareness campaigns, and research and development play a vital role in fostering social acceptance, technology adoption, and optimizing biogas production processes. Collaborative efforts among the government, private sector, and local communities are recommended to ensure wide-scale adoption of biogas, promoting economic, social, and environmental sustainability. By enabling informed decision-making, this research supports the transition to renewable energy sources and the achievement of sustainable development goals (SDGs), with a particular focus on bioenergy. The aim of this study is to explore the challenges and opportunities associated with biogas production in Colombia, including technical, economic, social, and environmental aspects, and provide recommendations for promoting its sustainable implementation and widespread adoption in the country.

Keywords: anaerobic digestion; bioenergy; South America; zero-waste; bioeconomy; biogas; SDG

1. Introduction

Due to the high demand for fossil fuels and their impact on climate change, energy generation by means of renewable energy sources from residual biomass has received increased attention as a promising alternative to meet the growing energy demand and help mitigate the adverse impacts of global warming. Residual biomass and its conversion into biogas is a sustainable and widely adopted technology for generating renewable energy.

The current application of biomass for energy purposes in developing countries faces several limitations. Firstly, there is inefficient exploitation, particularly prevalent in sub-Saharan African and Latin American nations, leading to forest degradation and adverse effects on climate, human health, and social well-being. Additionally, the reliance on wood as a primary biomass source poses a risk of deforestation in the future. Biomass plants also require significant space, posing challenges in urban areas. Furthermore, biomass energy is generally less efficient than fossil fuels, and certain biofuels, such as ethanol, have lower efficiency compared to gasoline. Biomass energy also faces competition with other renewable fuels, and its production can be costly. Moreover, biomass energy production requires water, adding to its resource requirements [1,2].

The potential for biogas generation in Colombia is substantial due to the wealth of natural resources, particularly residual biomass that can be used as feedstock [3]. Agricultural waste, food waste, and livestock manure are just a few examples of the sources of this residual biomass. To drive the growth of renewable energy, including biogas, the Colombian government has implemented policies and incentives [4]. The results have been substantial, with rapid growth in the development and production of biogas projects over the last decade.

The socio-economic opportunities associated with biogas production in Colombia include job creation, increased local energy independence, and improved rural livelihoods. Biogas plants provide employment opportunities in the operation, maintenance, and management of the facilities and provide a source of income for farmers and communities who sell their residual biomass to the plants [5]. In addition, biogas production reduces dependence on imported energy sources, thus improving energy security and reducing energy costs [6]. Moreover, the development of biogas projects in rural areas can improve the livelihoods of local communities by providing a source of clean energy and reducing environmental pollution [7].

The progression in technology has greatly impacted the growth of biogas production in developing countries. The enhanced design and functioning of biogas plants has reduced production costs, thereby making biogas a more feasible energy source compared to conventional sources. The advent of advanced feedstock treatment and digestion technologies has broadened the scope of usable residual biomass as feedstock, thereby boosting the potential for biogas generation [6–9].

Regardless of the recent developments in the biogas industry, in the specific case of Colombia, many difficulties remain, including the affordability compared with conventional energy sources. Factors such as feedstock collection, transportation, processing, plant construction, and operation represent a high cost for biogas production [10]. Moreover, the effective operation of biogas plants also poses technological challenges, requiring skilled personnel, cost-efficient technology, and effective maintenance and management systems [11].

The utilization of biogas as a sustainable energy source encounters various social challenges that require a comprehensive approach involving public awareness, education, cultural barriers, technology access, financial resources, and governmental support.

In terms of technology development and accessibility, household biodigesters in Latin America and developing countries are designed based on local climate, organic waste availability, and materials and skills. Biodigesters are commonly used in rural and small communities with limited access to traditional energy sources, and biogas can be used for cooking, heating, or electricity generation [7].

Reducing greenhouse gas emissions and managing residual biomass and by-products are critical for sustainable biogas production due to their environmental impacts, including methane release and potential soil and water contamination [12].

The development of biogas production has the potential to fulfill partially and diversify the energy matrix while providing a clean fuel alternative; additionally, it will create employment opportunities and improve rural livelihoods [13].

Although biogas production has significant environmental benefits, its production cost at an industrial scale poses a considerable challenge for low-income countries like Colombia. The cost of implementing and maintaining biogas production systems is often too expensive to afford, impeding their ability to adopt this sustainable energy solution. Technological and environmental challenges associated with biogas production must also be addressed to ensure its sustainable development. Further research is needed to gain a better understanding of the opportunities and challenges associated with biogas production in Colombia and to develop effective strategies for promoting its sustainable development [10].

This study aims to investigate and address the social, technological, and environmental challenges related to biogas deployment in Colombia, focusing on promoting sustainable production, informing policymakers, and assessing socio-economic impacts. It involves investigating social acceptance barriers, enhancing public perception, identifying efficient production processes and strategies to reduce greenhouse gas emissions, providing insights for policymakers and investors, and assessing the socio-economic impacts of biogas production.

2. Status of Bioenergy Production

The utilization of bioenergy, derived from organic matter such as crops, wood, and waste, is gaining recognition as a sustainable energy source with potential to mitigate the negative impacts of greenhouse gas emissions and dependence on fossil fuels. The trend of growth in global bioenergy production is steady, with estimations suggesting a considerable potential for expansion in the future [14]. According to the International Energy Agency, the contribution of bioenergy to the total primary energy supply was estimated to be 10% in the year 2019. Primarily, solid biomass is the dominant form of bioenergy, and it is widely utilized for heating and cooking purposes in developing countries [15]. However, the adoption of liquid biofuels, such as bioethanol and biodiesel, in the transportation sector is also on the rise [16]. Along with conventional bioenergy sources, the development of advanced biofuels, such as those produced from algae and woody biomass, is garnering increasing attention due to their potential to increase bioenergy production while simultaneously reducing greenhouse gas emissions and land use impact [17].

Leading nations in bioenergy production include the US, Brazil, and China. The US dominates in biofuels, mostly from corn and soybeans, while Brazil leads in bioethanol from sugarcane [14]. China stands out in solid biomass production, primarily from crop residues and forest biomass. Germany, China, and Sweden top the biogas production chart, with China having the most biogas plants globally and a major focus on renewable energy. Biogas production in China primarily originates from livestock manure and food waste digestion [18]. Germany is the second largest biogas producer from agricultural crops and organic waste. Biogas production in Germany primarily comes from agricultural crops and organic waste [19]. Sweden, with its focus on sustainable waste management, ranks third in biogas production, mostly from organic waste digestion [20]. Other significant biogas-producing nations include the US, Italy, and the UK. Biomass characteristics and sources can also impact data on the number of bioenergy power plants and its production. Leading bioenergy capacity nations are depicted in Figure 1.

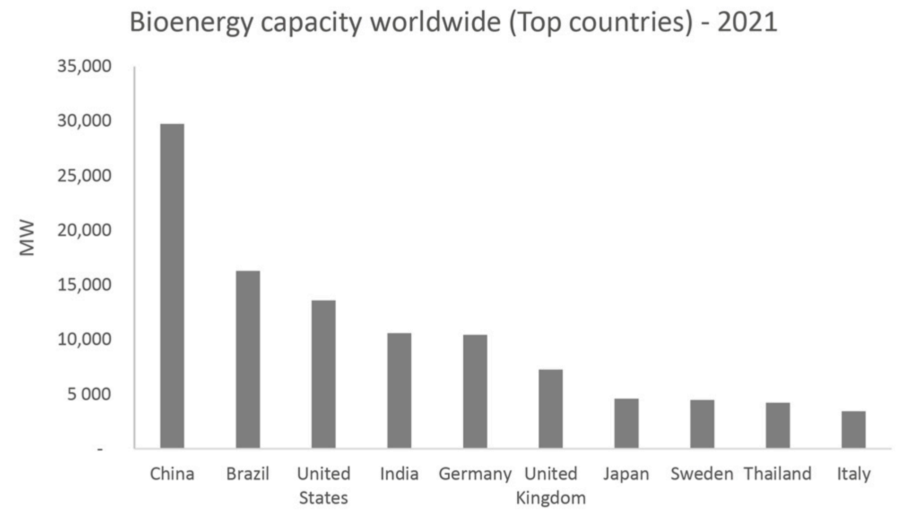

Figure 1. Bioenergy capacity worldwide. Source: Adapted from Duarah et al. [14].

In Latin America, biofuels like ethanol and biodiesel are widespread. Sugar cane is the primary source of ethanol production in Brazil and Colombia, with Brazil leading in production and export. Recently, there has been a rise in Colombia's ethanol production from sugarcane [16]. Argentina and Brazil are the leading producers of soybean and palm oil-based biodiesel, respectively, with both nations boasting substantial agriculture industries and being significant exporters of soybeans and palm oil. Other biofuels such as biogas and biojet fuel are generated in minor quantities in Latin America. Biogas is mostly generated from livestock manure and organic waste in countries like Mexico and Colombia, while biojet fuel is primarily produced from sugarcane in Brazil, serving as a power source for aircrafts [21]. Figure 2 displays the energy production capacity of biogas in Latin America and the Caribbean.

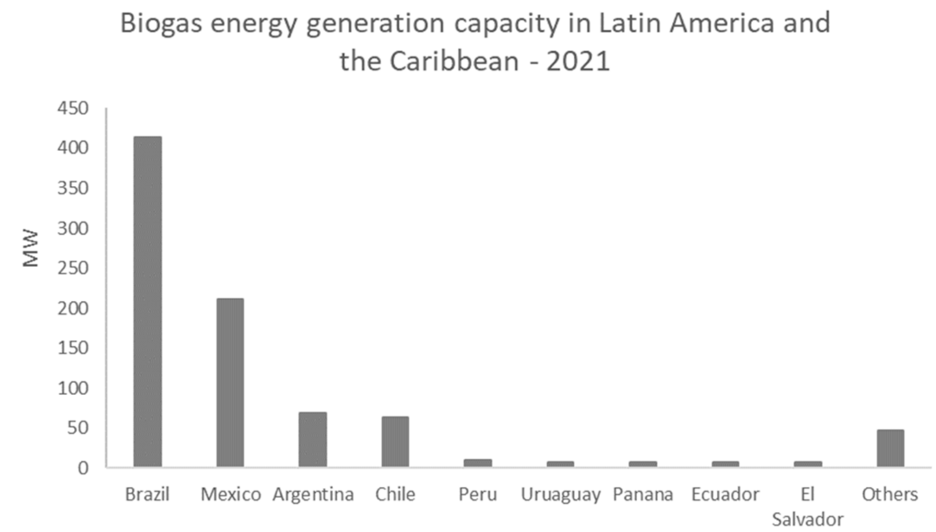

Figure 2. Biogas energy generation capacity in Latin America and the Caribbean. Source: Adapted from Duarah et al. [14].

2.1. Sustainability of Biomass Resources

Bioenergy has been acknowledged as a sustainable energy source due to its potential to decrease greenhouse gas (GHG) emissions and reduce dependence on fossil fuels. However, the sustainable availability and development of biomass resources is a multifaceted and complex issue that demands a comprehensive examination of environmental, social, economic, and political factors [22]. A crucial determinant of the sustainability of biomass resources is the accessibility of land and water resources. The cultivation of crops for bioenergy, such as corn and soybeans, can compete with food production for these resources. Additionally, the conversion of natural ecosystems, such as forests, to bioenergy crops can have adverse effects on biodiversity and carbon sequestration [23].

The sustainability of bioenergy is also dependent on its environmental and social impact. Unsustainable practices, such as large-scale cultivation of bioenergy crops, deforestation, and the displacement of communities, can result from bioenergy production [24]. Chemical inputs like fertilizers and pesticides can also harm air and water quality. However, bioenergy sustainability can be improved by using sustainable techniques, such as agroforestry, utilizing marginal and degraded lands, and utilizing waste and residue as feedstocks [25]. Advanced biofuels, such as those made from algae and woody biomass, can also have lower environmental and social impacts compared to conventional biofuels.

2.1.1. Economic Overview

Economic viability is a critical factor for biofuels to establish themselves as a sustainable energy source. While biofuels are seen to decrease GHG emissions and reduce reliance on fossil fuels, their economic sustainability is a complex matter shaped by various elements such as feedstock accessibility, production expenses, and government policies [10].

The cost of feedstocks, such as corn and sugarcane, plays a significant role in the economic sustainability of biofuels and can be impacted by factors like weather conditions, crop yields, and global demand. Additionally, the cost of converting these feedstocks into biofuels can differ based on the technology and efficiency of the production process. Moreover, competition with food production is another concern, as the use of food crops as biofuel feedstocks (e.g., corn and sugarcane) can result in rising food prices and decreased food security [26].

Government policies and regulations also have a considerable impact on the economic sustainability of biofuels. Policy measures such as subsidies and mandates for biofuels can aid in establishing markets and lowering production costs, but they can also lead to economic imbalances and limit incentives for innovation [27].

2.1.2. Social Overview

The impact of the rise of biofuels on energy production is significant, and the social consequences of biofuels cannot be ignored. Land use changes, displacement of local communities, and violations of human rights and labor conditions are among the far-reaching effects of biofuels [7].

One of the most alarming social impacts of biofuels is the displacement of local communities. The conversion of natural habitats like forests into bioenergy crops often forces indigenous and traditional communities to leave their homes, disrupting their livelihoods and way of life. This can also lead to social conflicts such as land grabbing and disputes over land ownership [28].

The production and use of biofuels also pose threats to human rights and labor conditions. The use of hazardous chemicals like pesticides and fertilizers can put workers' health and safety at risk, and there have been reports of child and forced labor in some countries [29]. To ensure that biofuels are socially sustainable, policies and regulations must be put in place to protect the rights and well-being of local communities and promote fair labor practices. Utilizing sustainable feedstocks, such as waste and residues, and avoiding the conversion of natural ecosystems into bioenergy crops are crucial steps in this direction [30].

2.1.3. Environmental Overview

The environmental aspect of biofuels is critical to their acceptance as a sustainable energy source. Complex environmental factors, such as feedstock source, production techniques, and land usage shifts, shape the environmental sustainability of biofuels.

Biofuels have the potential to create environmental concerns, including competition for land and water resources with food production. Large-scale cultivation of bioenergy crops, like corn and soybeans, can result in deforestation and land use changes, negatively impacting biodiversity and carbon sequestration, as well as cause water scarcity and degradation [31].

While biofuels can decrease GHG emissions in the transportation sector, the emissions generated by their production, such as land use changes and fertilizer usage, can counteract these reductions, making the environmental impact of biofuels a multifaceted issue that demands a comprehensive examination [32].

To attain environmental sustainability in biofuels, the adoption of sustainable feedstocks like waste and residues, along with policies and regulations promoting sustainable production methods, are key considerations. Additionally, advanced biofuels, like algae-based options with lower environmental impacts compared to traditional biofuels, deserve greater attention in the biofuels industry [33].

2.1.4. Political Overview

The political viability of biofuels globally is a multi-faceted and constantly changing topic. On the one hand, governments see the benefits of biofuels in reducing reliance on fossil fuels, reducing GHG emissions, boosting rural development, and creating jobs, and therefore have implemented policies such as blending mandates, subsidies, and tax incentives to support the growth of the biofuels industry [34].

However, studies conducted by Lazaro et al. [35] reported that biofuels are also facing criticism over potential negative consequences such as food insecurity, deforestation, and land usage. Takaes et al. [36] argue that the use of land for biofuel production may cause food shortages, higher food prices, and environmental degradation. Additionally, the extent to which biofuels decrease GHG emissions is still under investigation, with some research indicating limited impact. The political sustainability of biofuels has also been impacted by trade policies; for instance, the US and EU have encouraged the use of biofuels to increase energy independence and reduce reliance on foreign oil, but these policies have been criticized for benefiting domestic biofuel industries at the expense of industries in developing nations [35].

2.2. Importance of Residual Biomass Transformation Technologies

Biofuel transformation technologies are dynamic and constantly advancing, with new advancements and innovations being made. Upgraded technologies focus on converting sources like corn, sugarcane, and algae into biofuels like ethanol, biodiesel, and biogas through methods like fermentation, bioconversion, hydrolysis, thermochemical conversion, and newer techniques like enzymatic conversion and synthetic biology [37–40].

The future of biofuel transformation technologies is promising as it keeps advancing and becoming more efficient due to the emerging need for renewable energy and the requirement to decrease GHG emissions. The growth of these technologies is expected to be accelerated by the abundance of data and state-of-the-art computational tools [38].

However, studies conducted by Takaes et al. [36] have pointed out that political and economic factors are expected to impact the future of biofuel transformation technologies, as those variables influence investment and growth in the sector.

2.2.1. Bioenergy Production by Thermal Methods

Thermal conversion methods are being utilized more frequently for bioenergy production, converting biomass into energy through heat. As shown in Table 1, techniques like combustion, gasification, pyrolysis, and co-firing are seen as cost-effective and efficient ways to harness energy from local sources like agricultural waste in developing countries.

Table 1. Biomass thermal conversion technology.

Technology	Definition	Common Fuel Used	Reference
Combustion	The process of burning biomass to produce heat and electricity.	Wood, wood waste, agricultural residues, and energy crops.	[41]
Gasification	The process of converting biomass into a gaseous fuel, typically syngas.	Wood, wood waste, agricultural residues, and energy crops.	[42,43]
Pyrolysis	The process of heating biomass in the absence of oxygen to produce a liquid biofuel, typically bio-oil.	Wood, wood waste, agricultural residues, and energy crops.	[44,45]
Co-firing	The process of using biomass along with fossil fuels, such as coal, to generate electricity.	Wood, wood waste, agricultural residues, and energy crops. However, the fuel used in co-firing is mostly dependent on the type of fossil fuel used.	[44,46]

Source: the authors.

However, these methods may face difficulties in implementation and development in some developing nations due to the need for high capital investments, high operational costs, and limited advanced infrastructure and technology.

2.2.2. Bioenergy Production by Biochemical/Chemical Methods

Biochemical/chemical conversion methods are a way to produce bioenergy by using chemical and biological reactions to convert biomass into a usable form of energy. These methods include transesterification, synthetic biology, anaerobic digestion, and enzymatic conversion.

The methods presented in Table 2 offer a cost-effective and efficient way to generate energy from local resources, like agricultural waste, in developing countries. However, their implementation and development can be limited by high capital and operational costs, as well as the lack of necessary infrastructure and technology. This lack of economic resources can make it difficult to establish and maintain biochemical/chemical conversion facilities, and the absence of skilled labor and access to advanced technology and research may limit the growth of the bioenergy production sector in some developing nations [26]. Addressing these challenges is important for promoting the growth of the bioenergy industry in developing countries and should be a priority for governments and other stakeholders.

Table 2. Biomass biochemical/chemical conversion technology.

Technology	Definition	Fuel Used	Reference
Transesterification	The process of converting fats or oils into methyl esters (biodiesel) by reacting with an alcohol, typically methanol or ethanol.	Lipid-rich feedstocks such as vegetable oils, animal fats, and waste cooking oils.	[47,48]
Synthetic Biology	The field of biology that involves the design, construction, and manipulation of biological parts, devices, and systems that do not occur naturally.	Various microorganisms, mainly algae, to produce biofuels such as bioethanol and biodiesel.	[49]
Anaerobic Digestion	The process of breaking down organic matter in the absence of oxygen to produce biogas, a mixture of methane and carbon dioxide.	Organic waste, such as food waste, agricultural waste, and sewage sludge.	[50]
Enzymatic Conversion	The process of using enzymes to convert biomass into a usable form of bioenergy, such as bioethanol or biogas.	Various types of feedstocks, such as lignocellulosic materials, such as agricultural waste and woody biomass, as well as starchy and sugary materials like corn and sugarcane.	[51]

Source: the authors.

Results from Scown et al. [52] argue that the development of bioenergy through biochemical/chemical conversion methods is of interest to many developing countries despite the inherent challenges. Innovations and advancements, as well as increased funding and support, may help alleviate some of these challenges and enable more countries to adopt these methods. The relevance of a particular bioenergy production method for a country depends on various factors, including the availability of local resources, market demand, and government policies.

In Latin America, the adoption of bioenergy technology is primarily based on residual biomass from the agriculture sector, livestock, and wastewaters. These resources are abundant and widely available in the region, making them suitable feedstocks for bioenergy production. Additionally, biofuels produced in the region can be summarized as follows [53]:

Latin America's biofuels can be categorized as sugarcane-based ethanol, biogas, forest-based bioenergy, and microalgae-based biofuels. Sugarcane-based ethanol is well-established and cost-effective, particularly in Brazil and Colombia. Biogas is advantageous in countries with high livestock populations and abundant organic waste. Forest-based bioenergy utilizes wood residues and forest biomass, contributing to sustainability and biodiversity preservation. Abundant sunlight and water resources create an ideal environment for microalgae cultivation, offering vast potential across various industries. The factors driving the successful adoption of bioenergy technologies in Latin America include the country's specific resources, energy needs, and government policies. For instance, Cherubin et al. [54] argue that countries rich in sugarcane and with a well-established ethanol production infrastructure may find that sugarcane-based ethanol is the most feasible bioenergy technology due to the availability of feedstocks and established production facilities, making it a cost-effective and efficient option. Meanwhile, Kabeyi et al. [55] propose that biogas can be a more appealing option for countries with a high potential for organic waste generation, especially those with large livestock populations, while Jankovský et al. [56] and Sallustion et al. [57] move towards the perspective that forest-based bioenergy may be a suitable choice for countries with vast tropical forests. The selection of the most appropriate bioenergy technology will depend on the unique circumstances of each country.

3. Potential Opportunities in Biomass Conversion from Biological Methods

3.1. Potential Biomass Feedstocks in Colombia

Residual biomass as a feedstock for biogas production in Colombia can be classified into five categories, including agricultural waste, livestock manure, organic municipal waste, industrial wastewaters, and energy crops. The utilization of these feedstocks in Colombia holds tremendous potential to not only reduce waste volume and mitigate environmental impact but also to generate clean energy, paving the way for a significantly more sustainable energy matrix [13].

Agricultural waste, comprising flowers, panela cane, palm fiber, potato, beans, and corn stalks, is a readily accessible and economically feasible source for biogas production in Colombia. The convenient collection and transportation of these feedstocks to biogas facilities for anaerobic digestion has resulted in their growing utilization in biogas production [6,8].

The livestock sector plays a considerable role in manure generation in Colombia, primarily from cattle, pigs, and poultry. Utilizing livestock manure as a source for biogas production offers various advantages, such as reducing odors, pathogens, and environmental pollution associated with conventional manure disposal methods. Additionally, the use of stabilized manure as a feedstock can enhance soil health and fertility through the application of digestate, which acts as a fertilizer residue [58,59].

Organic municipal waste as a feedstock for biogas production can help reduce waste volume and produce clean energy. However, managing organic municipal waste in Colombia can be challenging, with a large portion of it being landfilled.

Incorporating energy crops like jatropha, sweet sorghum, and elephant grass in the energy mix can offer diversification by generating biogas. These crops grow rapidly and can be grown in marginal or degraded lands. Table 3 presents comprehensive information on the biogas energy potential of various residues, including municipal wastewater, agricultural waste, food waste, and livestock manure. The data include the biomass produced, the biogas yield per ton of residues, and the methane concentration, providing valuable insights into the biogas production potential from different residues and aiding in the selection of the most suitable residue for biogas generation.

Table 3. Potential biogas energy generation from different substrates/feedstocks available in Colombia.

	Municipal Wastewater								
	Bogotá	**Medellín**	**Cali**	**Barranquilla**	**Cartagena**	**Cucuta**	**Soledad**	**Ibague**	**Bucaramanga**
Volume per year	520,684	161,236	154,518	80,414	63,550	41,597	40,722	34,640	34,533
Biogas yield (m^3/year)	27,196,203	8,421,626	8,070,723	4,200,192	3,319,307	2,172,669	2,126,985	1,809,293	1,803,721
Biogas energy yield (TJ/year)	634	196	188	98	77	51	50	42	42
		Livestock							
	Poultry	Swine	Bovine						
Total manure (ton/year)	6,619,942	2,745,392	83,497,181						
Methane yield (m^3/year)	238,317,928	115,306,473	2,003,932,344						
		Agricultural							
	Rice	Plantain	Coffee	Corn					
Production (ton/year)	2,078,073	310,192	859,185	912,659					
Methane yield (m^3/year)	438,888,968	233,880	4,484,945	225,171,298					

Source: the authors. Adapted from TECSOL [60].

3.2. Adoption of Traditional Bioenergy Technologies

3.2.1. Conventional Anaerobic Digesters in Emerging Countries

In Latin America, and in developing countries worldwide, the design of household digesters is dependent on climate conditions, organic waste availability, and the materials and skills available locally. Fixed dome, floating drum, and tubular digesters are the most common models employed in rural areas of developing countries to suit the conditions of Latin America. Table 4 presents an overview of the most common biodigesters utilized in rural areas of Colombia, including a concise description of their operational advantages and disadvantages.

Table 4. Operational advantages and disadvantages of commonly used anaerobic digesters in rural areas in Colombia.

Biodigester Technology	**Fabrication Materials**	**Temperature Requirements**	**Advantages**	**Disadvantages**	**Geographical Implementation**	**Other Considerations**
Fixed dome biodigesters	Bricks Cement Concrete Polymers Glass-fiber-reinforced plastics	Underground construction. Unaffected by temperature variations.	High biogas production. Less maintenance than other types of biodigesters. Quick and easy installation. Constructed with durable materials built to last for many years. Suits a variety of applications. Supports higher gas pressure than tubular and floating drum biodigesters. Self-agitated by biogas pressure.	More expensive than other types of biodigesters, making them a less cost-effective option. Limited capacity when compared to other types of biodigesters. Fragile and can be damaged easily if not handled correctly. Less efficient than other types of biodigesters. Poor performance in cold climate conditions.	China India Nepal Uganda Tanzania	Lifespan: over 20 years if maintenance is guaranteed. Construction time: approx. 18 days.

Table 4. *Cont.*

Biodigester Technology	Fabrication Materials	Temperature Requirements	Advantages	Disadvantages	Geographical Implementation	Other Considerations
Floating drum biodigesters	Bricks and concrete for digester Metal for drum High-density Polyethylene	It requires warm conditions for its optimal operation.	Cost-effective solution as it requires minimal maintenance. Quick and easy installation. High capacity when compared to other types of biodigesters. Medium biogas production.	Fragile and can be damaged easily if not handled correctly. Poor performance in cold climate conditions. Biogas leakages may occur. Requires manual steering.	India	Lifespan: 20 years if maintenance is guaranteed. Construction time: approx. 18 days.
Tubular biodigesters	Polyethylene Poly vinyl chloride High-density polyethylene Glass-fiber-reinforced plastics	Structures are easily heated due to their thin walls. Built partially underground.	Low-cost solution. Low-maintenance biodigester compared to others. Versatile and easy to install. Construction with low-cost materials.	Low biogas production. Easily damaged by external factors. Biogas leakages may occur. Steering not possible.	South America Africa South Asia	Lifespan: 2 years if exposed to the sun. Between 2 and 5 years if maintenance is guaranteed. Construction time: approx. 2 days.

Source: the authors. Adapted from Rodríguez-Nuñez et al. [61], Ahmed et al. [62], and Abubakar A. [63].

3.2.2. Alternative Energy Sources from Biogas

Biogas has versatile applications as an alternative fuel. It can be directly used as compressed biomethane gas (CBM) or blended with natural gas for transportation, generate electricity in combined heat and power (CHP) plants, provide thermal energy for industrial processes, or be distributed through natural gas networks for heating homes and buildings.

Likewise, electricity generation through the metabolic activity of microorganisms has gained considerable interest in the academic community as a potential alternative to traditional energy sources. Lohani et al. [31] attribute this observable fact to the increasing need for sustainable and renewable energy solutions to mitigate the negative environmental impacts of fossil fuel consumption. The utilization of the metabolic processes of microorganisms to produce electricity through chemical reactions has emerged as a promising area of research. Murugaiyan et al. [64] and Tawalbeh et al. [65] have conducted research studies on methods that have garnered increasing attention in the academic community and evaluate the following techniques:

Bioelectrochemical systems (BES) consist of different technologies that utilize microorganisms to convert chemical energy into electrical energy by means of a series of electrochemical reactions. These systems typically consist of an anode and a cathode separated by a membrane, allowing the transfer of electrons or ions. Microbial Fuel Cell (MFC) and Microbial Electrolysis Cell (MEC) are the most studied bioelectrochemical technologies.

MFC is a specific type of BES that converts the metabolic activity of microorganisms directly into electrical energy. Microorganisms in the anode compartment oxidize organic matter, releasing electrons and protons. The electrons flow through an external circuit to the cathode, generating electrical current, while the protons migrate through the membrane to the cathode, where they combine with the electrons and an electron acceptor to form water. Some of the most common substrates studied include organic substrates such as acetate, cellulose, glucose, landfill leachate, macro algae, micro algae, sucrose, and various types of wastewaters [66,67]. For the case of MEC, it employs microorganisms to drive the electrolysis of water, producing hydrogen gas (H_2) or other desired products. In a MEC, an external voltage is applied which facilitates the transfer of electrons from the anode to the cathode. The electrons are used to reduce protons at the cathode, forming hydrogen gas [68].

Proton exchange membrane fuel cell (PEMFC) is a system presented in a research study conducted by Guan, T. et al. [69] that utilizes biogas generated from the anaerobic digestion of organic waste from a dairy farm as the hydrogen source for the fuel cell. In this process, methane is supplied to the anode of the PEMFC, where it undergoes oxidation, releasing electrons that travel through an external circuit, thereby generating electricity. Simultaneously, positively charged hydrogen ions are generated and traverse the proton exchange membrane to reach the cathode. At the cathode, it combines with oxygen and electrons, forming water and thus completing the electrical circuit.

Biogas steam reforming is a process used to produce hydrogen gas from biogas. In this process, the biogas is reacted with steam at high temperatures, typically in the presence of a catalyst, to produce a mixture of carbon monoxide and hydrogen. Nickel is commonly used as a catalyst for hydrogen production. Other catalysts, such as cobalt (Co) and iron (Fe), are also used in biogas steam reforming, but nickel is the most widely used due to its favorable properties. The choice of catalyst depends on various factors such as the composition of the biogas feedstock, operating conditions, and the desired product quality. Syngas can then be further processed to separate the hydrogen and remove impurities. The resulting high-purity hydrogen can be used as a fuel for transportation, heating, or power generation, or as a feedstock to produce chemicals and fertilizers [70].

Alkaline water electrolysis processes consist of a method in which biogas is used to generate electricity, which is then used to split water into hydrogen and oxygen through electrolysis. The electrolysis takes place in an alkaline solution, which acts as an electrolyte, facilitating the ion transfer and increasing the efficiency of the process [71].

Chemical looping is a process that involves the use of a solid material, called the oxygen carrier, to transfer oxygen from the air to a fuel source in a reactor. In a chemical looping system based on biogas production, biogas produced through anaerobic digestion of organic waste is used as the fuel source. The biogas is fed into a reactor where it reacts with the oxygen carrier, transferring oxygen to the fuel and producing a mixture of carbon dioxide and hydrogen. The carbon dioxide can then be separated and stored or utilized for various applications, while the hydrogen can be utilized as fuel in a fuel cell or other energy conversion system. This method stands as a sustainable and renewable energy source, converting waste into useful energy while also reducing the carbon footprint through the separation and utilization of carbon dioxide [72].

3.3. Socio-Economic and Environmental Benefits

The rural farmer population in Colombia, known as campesinos, exhibits a variety of socio-economic characteristics. A significant number of them face challenges such as poverty, limited land access, restricted market opportunities, inadequate infrastructure, limited access to education and healthcare services, as well as exposure to armed conflict. Nevertheless, multiple programs and policies aimed at improving the lives and livelihoods of rural farmers in Colombia, such as sustainable agriculture support, secure land ownership, and market access, are being executed [73].

Poverty is a prevalent issue within the rural sector in Colombia, which has a significant impact on the adoption of technology in developing countries. Studies conducted by Khan et al. [74] identified that poverty can limit an individual's ability to access and afford new technologies in rural areas. In addition, the authors listed the factors contributing to this phenomenon, which include limited access to capital, education, and skills, as individuals living in poverty may not possess the financial resources necessary to invest in new technologies, such as purchasing a computer or paying for internet access. Additionally, the ongoing costs associated with using new technologies, such as service and maintenance, may be unaffordable for individuals living in poverty, and they may also not understand the potential benefits of these technologies in terms of improving their lives and livelihoods. Mendieta et al. [7], Puzzolo et al. [26], and Sarker et al. [75] have studied the barriers of technology adoption in developing countries created by poverty. In their studies, there are stated strategies to improve access to technology for individuals living in poverty, such as the utilization of digital financial services, mobile technologies, and digital literacy programs.

The utilization of biogas production in Colombia holds the potential to act as a catalyst for socio-economic growth in various ways, including job creation, income generation, energy security, rural development, and decreased costs associated with imports [76].

4. Challenges and Barriers for Biogas Production in Colombia

4.1. Centralized Residual Biomass Biorefineries

The centralization of solid waste for biogas production brings significant advantages that lead to increased efficiency, as it allows for the collection of a greater amount of organic waste in one location. This strategy increases the efficiency of the biogas production process, reduces transportation costs, and facilitates access to the waste. Additionally, it generates greater sustainability as the waste is handled safely, reducing leaks of methane and other greenhouse gases into the atmosphere. The report presented by the OECD in 2021 [77] demonstrated that the centralization also allows for better quality control in the biogas production process as the waste can be classified and selected more accurately.

Based on the theoretical potential of biogas production in Colombia at 149,436 TJ/year and the estimated technical potential of 53,554 TJ/year, centralized waste management could be an energy solution that would equate to 25% of the demand for natural gas in Colombia in 2016 [3]. Furthermore, it is estimated that the potential of confined livestock farming would represent approximately 50% of this percentage. Large-scale biogas production plants, with daily production exceeding 1000 m^3/day of biogas, are shown in the Figure 3.

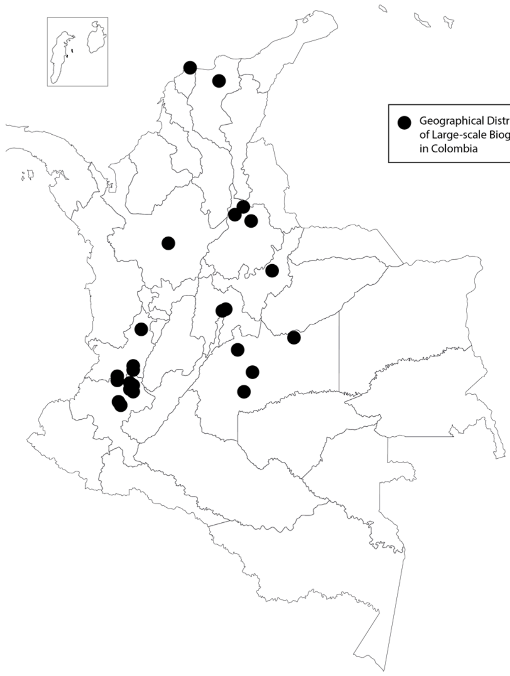

Figure 3. Large-scale biogas plants in Colombia. Source: the authors. Adapted from Ali et al. [78].

4.2. Techno-Economic Biodigester Implementation Approach

Performing a techno-economic approach to biodigester implementation is a critical method for ensuring its success. This approach involves conducting a feasibility study, including the analysis of local conditions, resources, and biodigester potential, and a cost-benefit analysis to determine its economic viability. Based on the study results, the most suitable technology is selected and the biodigester is designed and engineered to meet specific project needs and requirements. The design and construction of the biodigester are performed with attention to material and equipment specifications and standards. The biodigester is then operated and maintained efficiently, with regular monitoring, troubleshooting, and repairs as needed. Performance assessments and cost evaluations are conducted regularly, and modifications and improvements are made to optimize the system. This approach integrates economic and technical analysis in biodigester implementation and ensures the system meets project and end-user needs. In this sense, process control is guaranteed to produce high-efficiency results.

4.2.1. Construction, Operation, and Maintenance

Anaerobic systems comprehend a range of scales, each with distinct operational characteristics and corresponding knowledge requirements. These systems are frequently installed to comply with environmental regulations and are sometimes donated by government entities. However, this lack of ownership often leads to their abandonment on farms, thereby transforming them into sources of pollution and frustration by farmers [26]. The costs associated with acquiring robust technologies limits small-scale agricultural producers from accessing them, leading them to opt for simple, low-cost, and low-efficiency systems. Similarly, more efficient technologies require knowledge and experience on the part of their operators, which increases risk in the operation and timely response to system failures. This is particularly pronounced in energy generation and automation systems.

After-sales service, particularly in small and isolated projects, increases costs and is difficult to obtain. There is also a perception of low monitoring after installation in publicly financed projects [78].

4.2.2. Investment

The utilization of organic residual biomass to produce biogas in Colombia presents significant challenges. One of the main obstacles is the acquisition of financial resources to cover the costs associated with the construction of a biogas plant, including the acquisition of equipment and the hiring of technical personnel. Despite the availability of various anaerobic digestion technologies, potential biogas project developers perceive a high investment cost, particularly when accounting for the additional costs associated with the refinement of gas and energy generation. The perception that these investment costs are not recoverable from the operation of a biogas plant is prevalent [79].

To mitigate the initial investment barrier, Law 1715 of 2014 established tax incentives that exempt the acquisition of equipment and consulting studies from the payment of value-added tax (VAT) and allow for a deduction of up to 50% of investment costs for 15 years. Later in 2020, the decree 829 of June 10th revoked articles 11, 12, 13, and 14 of Law 1715 of 2014, which established a new framework of incentives for the generation of electricity using non-conventional sources. However, this information and its applicability to biogas generation is not widely understood among agricultural or agro-industrial groups, particularly among small- and micro-businesses [80]. A lack of knowledge applies not only to tax incentives, but also to the financial structuring of biogas projects, which requires consideration of all revenues and avoided costs throughout the value chain. This includes costs associated with the treatment of residual biomass, the replacement of fuels, and the value of the digestate generated as a byproduct, as well as potential tax and other incentives. If these elements are not considered, the perception of a lack of return on initial investment will persist.

Micro-businesses, particularly in the agricultural sector, often perceive these technologies as an environmental requirement rather than a business opportunity. Farmers may be beneficiaries of state projects that install biodigesters but lack the capabilities to conduct technical and financial analysis of investments in this field. Small and medium-sized enterprises may be persuaded by the fact of making supplementary investments beyond their primary business focus. However, they must navigate the challenges posed by their own production priorities and time constraints, which may impede their ability to engage in such ventures. Micro-businesses generally do not have the ability to perform financial analysis or structure business plans to present the project to a bank that would allow them to obtain financing to implement the technology. Therefore, if it is an environmental obligation, users carry it out as an expense and do not quantify or maximize the use of the products obtained from the anaerobic digestion process. Figure 4 summarizes the opportunities of biogas production [79].

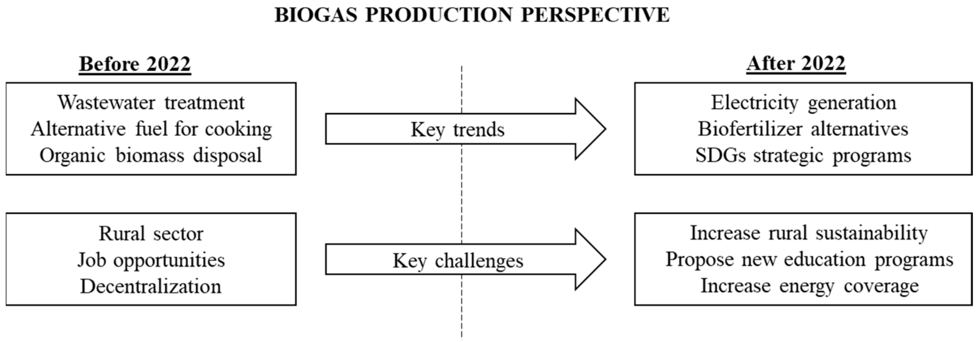

Figure 4. Biogas production perspectives in Colombia. Source: the authors.

4.2.3. Limited Experience with Biogas Projects Funders

Khan et al. [74] suggested that the limited experience of financial entities with biogas production projects presents a significant obstacle to the development of non-conventional sources of renewable energy. Investment funds have reported that many national and international resources remain untapped due to a lack of maturity in the project structure, which precludes the necessary risk analysis needed to allocate resources.

Sarker et al. [75], Ali et al. [78], and Mendieta et al. [7] highlight a deficiency of knowledge among biodigester developers; however, it is also apparent that project evaluators within financial entities, both public and private, lack a thorough understanding of anaerobic digestion technology. Unlike other technologies, such as solar or wind energy, anaerobic digestion is a comprehensive and multi-faceted technology that encompasses the various variables previously discussed [81]. This span of application, which can be an advantage in a circular economy analysis, can also present a challenge when evaluating financial analyses because of the complexity and interrelatedness of socio-economic, political, and environmental variables. In addition to direct revenue generation, there are also potential cost savings from biomass management, sales of the generated energy, savings on payments to third parties for self-generated energy, sales of digestate as fertilizer, and reductions in costs for purchasing fertilizer from third parties [31]. Additionally, there are potential revenues from avoided carbon taxes for the use of self-generated fuels, avoided fees for waste disposal, and other factors. This complexity poses a challenge for risk analysis, particularly for evaluators who lack knowledge of the technology.

4.3. Social Acceptance and Technology Adoption

The social acceptance and technology adoption of biogas production in Colombia are critical factors that determine the success of this renewable energy source in penetrating the Colombian energy market. However, to ensure widespread acceptance and adoption of biogas production, there are several obstacles that need to be addressed. These obstacles stem from factors such as the lack of awareness and education about the benefits of biogas production, inadequate infrastructure, and limited financing mechanisms in rural areas. Therefore, a coordinated effort between policymakers, investors, and local communities is required to promote the benefits of biogas production and overcome these obstacles. By leveraging policy incentives, financial support, and education efforts, biogas production can become a sustainable and widely adopted energy source in Colombia [7].

While there are significant obstacles that impede the adoption of biogas production in Colombia, drivers could be leveraged to promote its social acceptance and technology adoption. One such driver involves increasing awareness among local communities and stakeholders about the numerous benefits of biogas production, such as improved environmental sustainability, economic development, and energy security [26]. Based on this approach, policymakers could incentivize the development of biogas production by implementing supportive policies and regulations that eliminate financial barriers, stimulate investment, and promote technology adoption. These drivers, if utilized effectively, could help to propel the widespread adoption of biogas production in Colombia, making it an integral part of the country's renewable energy portfolio. Table 5 summarizes the obstacles and drivers to social acceptance and technology adoption of biogas production in Colombia:

Table 5. Obstacles and drivers to social acceptance and technology adoption of biogas production in Colombia.

Obstacles	**Levers**
Lack of awareness and education about biogas production	Promoting benefits of biogas production to local communities and stakeholders
Inadequate infrastructure for biogas production in rural areas	Implementing policies and regulations that incentivize biogas production
Limited or inaccessible financing mechanisms for small-scale farmers and rural communities	Providing financial support and access to financing mechanisms for biogas production

Source: the authors.

4.4. Research, Development, and Innovation Knowledge Gaps

Currently, waste utilization technologies are being used in the market for energy and fuel generation. Anaerobic digestion through specialized anaerobic organisms for biogas production still presents restrictions due to the complexity of the optimal biochemical reactions and their slow decomposition compared to other technologies. The study of pre-treatment technologies is of great importance in biogas production to establish the best alternatives to accelerate the process and ensure greater efficiency.

The existence of knowledge gaps regarding biogas production in Colombia has resulted in several challenges, such as limited access to infrastructure and technology, limited financing and investment, a shortage of professionals and experts, limited availability of suitable raw materials, social and cultural barriers to adoption, and insufficient regulations and policies. These obstacles delay project expansion and challenge the growth of a sustainable biogas industry [79].

The insufficient understanding of biomass residual utilization technology creates knowledge gaps that negatively impact research, development, and innovation efforts. This leads to the limited application of research outcomes and a limited impact on relevant sectors. Only large-scale projects with a need for automation and control processes tend to incorporate research findings to increase efficiency and allocate resources for research development. Meanwhile, the rural agricultural sector in remote and off-grid areas lacks access to critical technical information, preventing improvement of their biological processes and exploration through research, development, and innovation.

5. Conclusions and Recommendations

The emergence of bioenergy as a major contributor to the global energy mix highlights the need for research and development in advanced biofuels and sustainable production methods. Despite its potential to reduce greenhouse gas emissions, the impact of bioenergy on the environment, including land use changes, biodiversity, and water resources, must be evaluated and addressed to ensure its sustainable growth. In Latin America, the rapid growth of biofuel production presents a complex challenge, with concerns over environmental and social impacts, particularly land use changes, deforestation, and the displacement of local communities.

Biogas production from residual biomass presents a range of opportunities and challenges across the socio-economic, technological, and environmental spheres in Colombia. While the development of biogas production has the potential to create new employment opportunities and reduce the country's dependence on imported fossil fuels, there are also significant technological challenges to overcome, such as efficient biomass collection and processing. Additionally, effective waste management strategies must be implemented to mitigate negative environmental impacts. Nevertheless, biogas production has the potential to provide a sustainable source of energy while contributing to the reduction of GHG emissions, and as such, warrants further research and investment in Colombia.

This study highlights that the economic viability of biofuels is determined by feedstock accessibility, production costs, and government regulations. To ensure economic sustainability, it is necessary to utilize sustainable feedstocks, encourage innovation, and eliminate economic obstacles. The social sustainability of biofuels entails assessing the effects on land use, local communities, human rights, and labor conditions. Funding and support for bioenergy projects can overcome the challenges of high capital investments and operational costs. Access to advanced technologies and research can improve the efficiency and cost-effectiveness of bioenergy production.

This study concludes that the Colombian government can enhance the implementation of biodigesters by implementing a combination of tax incentives, subsidies, and grants. This financial support will assist in the installation and operation of biodigester systems. To promote the understanding and proper use of biodigesters, awareness campaigns should be organized to educate local communities on the benefits of biodigesters. Technical assistance should be provided to ensure the effective development and maintenance of the biodigester systems. Additionally, a partnership with the private sector can be established to advance the implementation of biodigesters in agriculture and livestock farming industries.

Future research should focus on:

- The deployment of biogas facilities in Colombia with regard to addressing social acceptance, technological advancements, and environmental challenges.
- Conducting further studies to develop more efficient and cost-effective processes for biomass collection, transportation, and processing.
- Carrying out research to identify and evaluate the most suitable waste management strategies for different regions in Colombia.
- Using research findings to inform policymakers and investors about effective and sustainable ways to promote biogas production in Colombia.
- Conducting additional studies on the socio-economic impacts of biogas production to understand its potential benefits and drawbacks for local communities.
- Aiming research efforts at promoting the sustainable deployment of biogas in Colombia, aligning with the country's broader goals of sustainable development (SDG), and combating climate change.

Author Contributions: Conceptualization, L.R.M. and M.L.-d.; Methodology, C.A.G. and S.V.M.; Software, C.A.G. and S.V.M.; Validation, C.A.G. and S.V.M.; Investigation, L.R.M., M.L.-d., A.M., J.S.-D.R. and L.E.C.-M.; Resources, A.M., J.S.-D.R. and L.E.C.-M.; Data curation, A.M., J.S.-D.R. and L.E.C.-M.; Writing—original draft, L.R.M. and M.L.-d.; Writing—review & editing, L.R.M. and M.L.-d.; Visualization, L.R.M. and M.L.-d.; Supervision, L.R.M. and M.L.-d.; Project administration, L.R.M. and M.L.-d.; Funding acquisition, L.R.M. and M.L.-d. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data available on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Majeed, M.T.; Luni, T.; Tahir, T. Growing Green through Biomass Energy Consumption: The Role of Natural Resource and Globalization in a World Economy. *Environ. Sci. Pollut. Res.* **2022**, *29*, 33657–33673. [CrossRef] [PubMed]
2. Pandyaswargo, A.H.; Wibowo, A.D.; Onoda, H. Socio-Techno-Economic Assessment to Design an Appropriate Renewable Energy System for Remote Agricultural Communities in Developing Countries. *Sustain. Prod. Consum.* **2022**, *31*, 492–511. [CrossRef]
3. Escalante Hernández, H.; Orduz Prada, J.; Zapata Lesmes, H.J.; Cardona Ruiz, M.C.; Duarte Ortega, M. *Atlas del Potencial Energético de la Biomasa Residual en Colombia*; Unidad de Planeación Minero Energética: Bogotá, Colombia, 2010; ISBN 9789588504599.

4. Unidad de Planeación Minero Energética. UPME Colombia Ley 1715 de 2014. In *Normatividad-UPME*; Unidad de Planeación Minero Energética: Bogotá, Colombia, 2014; Volume 13.
5. Rincón-Velásquez, N.Y.; Castiblanco-Rozo, C. Políticas y Normas Sobre Energías Renovables para el Desarrollo de Biogás en Colombia. Una Revisión. *Gestión Ambiente* **2021**, *24*, 98868. [CrossRef]
6. Garfí, M.; Castro, L.; Montero, N.; Escalante, H.; Ferrer, I. Evaluating Environmental Benefits of Low-Cost Biogas Digesters in Small-Scale Farms in Colombia: A Life Cycle Assessment. *Bioresour. Technol.* **2019**, *274*, 541–548. [CrossRef] [PubMed]
7. Mendieta, O.; Castro, L.; Vera, E.; Rodríguez, J.; Escalante, H. Toward the Adoption of Anaerobic Digestion Technology through Low-Cost Biodigesters: A Case Study of Non-Centrifugal Cane Sugar Producers in Colombia. *Water* **2021**, *13*, 2566. [CrossRef]
8. Luna-Del Risco, M.; Vásquez, A.J.; Zea Fernández, J.S.; Marín, E.; González, C.A.; Vargas, A.C.; Mejías Brizuela, N.Y. Biogas Production from the Specialized Dairy Farming and Porcine Subsectors in Antioquia, Colombia: Theoretical and Technical-Energy Potential Approach. *Agron. Res.* **2022**, *20*, 281–301. [CrossRef]
9. Durán Contreras, M.; Sequeda Barros, R.; Zapata, J.; Vanegas Chamorro, M.; Albis Arrieta, A. A Look to the Biogas Generation from Organic Wastes in Colombia. *Int. J. Energy Econ. Policy* **2020**, *10*, 248–254. [CrossRef]
10. Tavera-Ruiz, C.; Martí-Herrero, J.; Mendieta, O.; Jaimes-Estévez, J.; Gauthier-Maradei, P.; Azimov, U.; Escalante, H.; Castro, L. Current Understanding and Perspectives on Anaerobic Digestion in Developing Countries: Colombia Case Study. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113097. [CrossRef]
11. Gonzalez-Salazar, M.A.; Venturini, M.; Poganietz, W.R.; Finkenrath, M.; Kirsten, T.; Acevedo, H.; Spina, P.R. Development of a Technology Roadmap for Bioenergy Exploitation Including Biofuels, Waste-to-Energy and Power Generation & CHP. *Appl. Energy* **2016**, *180*, 338–352. [CrossRef]
12. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Household Anaerobic Digesters for Biogas Production in Latin America: A Review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 599–614. [CrossRef]
13. Jiménez Vásquez, A.F. Atlas Del Potencial Técnico-Energético Aprovechable Por Digestión Anaerobia de La Biomasa Residual Pecuaria Para Los Subsectores Porcícola y Ganadería de Leche Especializada En El Departamento de Antioquia. 2021. Available online: https://repository.udem.edu.co/bitstream/handle/11407/6604/T_MIU_504.pdf?sequence=1&isAllowed=y (accessed on 19 January 2023).
14. Duarah, P.; Haldar, D.; Patel, A.K.; Dong, C.D.; Singhania, R.R.; Purkait, M.K. A Review on Global Perspectives of Sustainable Development in Bioenergy Generation. *Bioresour. Technol.* **2022**, *348*, 126791. [CrossRef]
15. Angulo-Mosquera, L.S.; Alvarado-Alvarado, A.A.; Rivas-Arrieta, M.J.; Cattaneo, C.R.; Rene, E.R.; García-Depraect, O. Production of Solid Biofuels from Organic Waste in Developing Countries: A Review from Sustainability and Economic Feasibility Perspectives. *Sci. Total Environ.* **2021**, *795*, 148816. [CrossRef]
16. Cremonez, P.A.; Feroldi, M.; Feiden, A.; Gustavo Teleken, J.; José Gris, D.; Dieter, J.; De Rossi, E.; Antonelli, J. Current Scenario and Prospects of Use of Liquid Biofuels in South America. *Renew. Sustain. Energy Rev.* **2015**, *43*, 352–362. [CrossRef]
17. Ullah, K.; Kumar Sharma, V.; Dhingra, S.; Braccio, G.; Ahmad, M.; Sofia, S. Assessing the Lignocellulosic Biomass Resources Potential in Developing Countries: A Critical Review. *Renew. Sustain. Energy Rev.* **2015**, *51*, 682–698. [CrossRef]
18. China Statistics Press. Technology Industry. In *China Statistical Yearbooks Database*; China Statistics Press: Beijing, China, 2022.
19. Theuerl, S.; Herrmann, C.; Heiermann, M.; Grundmann, P.; Landwehr, N.; Kreidenweis, U.; Prochnow, A. The Future Agricultural Biogas Plant in Germany: A Vision. *Energies* **2019**, *12*, 396. [CrossRef]
20. Niskanen, J.; Magnusson, D. Understanding Upscaling and Stagnation of Farm-Based Biogas Production in Sweden through Transitional and Farming Logics. *J. Clean. Prod.* **2021**, *279*, 123235. [CrossRef]
21. Canabarro, N.I.; Silva-Ortiz, P.; Nogueira, L.A.H.; Cantarella, H.; Maciel-Filho, R.; Souza, G.M. Sustainability Assessment of Ethanol and Biodiesel Production in Argentina, Brazil, Colombia, and Guatemala. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113019. [CrossRef]
22. Kapoor, R.; Ghosh, P.; Kumar, M.; Sengupta, S.; Gupta, A.; Kumar, S.S.; Vijay, V.; Kumar, V.; Kumar Vijay, V.; Pant, D. Valorization of Agricultural Waste for Biogas Based Circular Economy in India: A Research Outlook. *Bioresour. Technol.* **2020**, *304*, 123036. [CrossRef]
23. Tamburini, E.; Gaglio, M.; Castaldelli, G.; Fano, E.A. Is Bioenergy Truly Sustainable When Land-Use-Change (LUC) Emissions Are Accounted for? The Case-Study of Biogas from Agricultural Biomass in Emilia-Romagna Region, Italy. *Sustainability* **2020**, *12*, 3260. [CrossRef]
24. Calvin, K.; Cowie, A.; Berndes, G.; Arneth, A.; Cherubini, F.; Portugal-Pereira, J.; Grassi, G.; House, J.; Johnson, F.X.; Popp, A.; et al. Bioenergy for Climate Change Mitigation: Scale and Sustainability. *GCB Bioenergy* **2021**, *13*, 1346–1371. [CrossRef]
25. Foong, S.Y.; Chan, Y.H.; Loy, A.C.M.; How, B.S.; Tamothran, A.M.; Yip, A.J.K.; Liew, R.K.; Peng, W.; Alstrup, A.K.; Lam, S.S.; et al. The Nexus between Biofuels and Pesticides in Agroforestry: Pathways toward United Nations Sustainable Development Goals. *Environ. Res.* **2022**, *214*, 113751. [CrossRef] [PubMed]
26. Puzzolo, E.; Pope, D.; Stanistreet, D.; Rehfuess, E.A.; Bruce, N.G. Clean Fuels for Resource-Poor Settings: A Systematic Review of Barriers and Enablers to Adoption and Sustained Use. *Environ. Res.* **2016**, *146*, 218–234. [CrossRef] [PubMed]
27. Hafid, H.S.; Omar, F.N.; Abdul Rahman, N.; Wakisaka, M. Innovative Conversion of Food Waste into Biofuel in Integrated Waste Management System. *Crit. Rev. Environ. Sci. Technol.* **2021**, *52*, 3453–3492. [CrossRef]
28. Bourdin, S.; Colas, M.; Raulin, F. Understanding the Problems of Biogas Production Deployment in Different Regions: Territorial Governance Matters Too. *J. Environ. Plan. Manag.* **2019**, *63*, 1655–1673. [CrossRef]

29. Tucho, G.T.; Moll, H.C.; Schoot Uiterkamp, A.J.M.; Nonhebel, S. Problems with Biogas Implementation in Developing Countries from the Perspective of Labor Requirements. *Energies* **2016**, *9*, 750. [CrossRef]
30. Obaideen, K.; Abdelkareem, M.A.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Maghrabie, H.M.; Olabi, A.G. Biogas Role in Achievement of the Sustainable Development Goals: Evaluation, Challenges, and Guidelines. *J. Taiwan Inst. Chem. Eng.* **2022**, *131*, 104207. [CrossRef]
31. Lohani, S.P.; Dhungana, B.; Horn, H.; Khatiwada, D. Small-Scale Biogas Technology and Clean Cooking Fuel: Assessing the Potential and Links with SDGs in Low-Income Countries—A Case Study of Nepal. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101301. [CrossRef]
32. Pizarro-Loaiza, C.A.; Antón, A.; Torrellas, M.; Torres-Lozada, P.; Palatsi, J.; Bonmatí, A. Environmental, Social and Health Benefits of Alternative Renewable Energy Sources. Case Study for Household Biogas Digesters in Rural Areas. *J. Clean. Prod.* **2021**, *297*, 126722. [CrossRef]
33. Abanades, S.; Abbaspour, H.; Ahmadi, A.; Das, B.; Ehyaei, M.A.; Esmaeilion, F.; El Haj Assad, M.; Hajilounezhad, T.; Jamali, D.H.; Hmida, A.; et al. A Critical Review of Biogas Production and Usage with Legislations Framework across the Globe. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 3377–3400. [CrossRef]
34. Bonaldo, C. Benefits of Blending Mandate in Sustainable Economies. In *New Metropolitan Perspectives*; Smart Innovation, Systems and Technologies; Springer: Cham, Switzerland, 2021; Volume 178, pp. 526–535. [CrossRef]
35. Lazaro, L.L.B.; Giatti, L.L.; Bermann, C.; Giarolla, A.; Ometto, J. Policy and Governance Dynamics in the Water-Energy-Food-Land Nexus of Biofuels: Proposing a Qualitative Analysis Model. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111384. [CrossRef]
36. Takaes Santos, I. Confronting Governance Challenges of the Resource Nexus through Reflexivity: A Cross-Case Comparison of Biofuels Policies in Germany and Brazil. *Energy Res. Soc. Sci.* **2020**, *65*, 101464. [CrossRef]
37. Bashir, M.A.; Wu, S.; Zhu, J.; Krosuri, A.; Khan, M.U.; Ndeddy Aka, R.J. Recent Development of Advanced Processing Technologies for Biodiesel Production: A Critical Review. *Fuel Process. Technol.* **2022**, *227*, 107120. [CrossRef]
38. Ambaye, T.G.; Vaccari, M.; Bonilla-Petriciolet, A.; Prasad, S.; van Hullebusch, E.D.; Rtimi, S. Emerging Technologies for Biofuel Production: A Critical Review on Recent Progress, Challenges and Perspectives. *J. Environ. Manag.* **2021**, *290*, 112627. [CrossRef] [PubMed]
39. Zhang, J.; Zhang, X.; Yang, M.; Singh, S.; Cheng, G. Transforming Lignocellulosic Biomass into Biofuels Enabled by Ionic Liquid Pretreatment. *Bioresour. Technol.* **2021**, *322*, 124522. [CrossRef] [PubMed]
40. Naji, S.Z.; Tye, C.T.; Abd, A.A. State of the Art of Vegetable Oil Transformation into Biofuels Using Catalytic Cracking Technology: Recent Trends and Future Perspectives. *Process Biochem.* **2021**, *109*, 148–168. [CrossRef]
41. Awogbemi, O.; Von Kallon, D.V.; Onuh, E.I.; Aigbodion, V.S. An Overview of the Classification, Production and Utilization of Biofuels for Internal Combustion Engine Applications. *Energies* **2021**, *14*, 5687. [CrossRef]
42. Narnaware, S.L.; Panwar, N.L. Biomass Gasification for Climate Change Mitigation and Policy Framework in India: A Review. *Bioresour. Technol. Rep.* **2022**, *17*, 100892. [CrossRef]
43. Jatoi, A.S.; Abbasi, S.A.; Hashmi, Z.; Shah, A.K.; Alam, M.S.; Bhatti, Z.A.; Maitlo, G.; Hussain, S.; Khandro, G.A.; Usto, M.A.; et al. Recent Trends and Future Perspectives of Lignocellulose Biomass for Biofuel Production: A Comprehensive Review. *Biomass Convers. Biorefinery* **2021**, *13*, 6457–6469. [CrossRef]
44. Mohamed, M.; Tan, C.K.; Fouda, A.; Gad, M.S.; Abu-Elyazeed, O.; Hashem, A.F. Diesel Engine Performance, Emissions and Combustion Characteristics of Biodiesel and Its Blends Derived from Catalytic Pyrolysis of Waste Cooking Oil. *Energies* **2020**, *13*, 5708. [CrossRef]
45. Hoang, A.T.; Ong, H.C.; Fattah, I.M.R.; Chong, C.T.; Cheng, C.K.; Sakthivel, R.; Ok, Y.S. Progress on the Lignocellulosic Biomass Pyrolysis for Biofuel Production toward Environmental Sustainability. *Fuel Process. Technol.* **2021**, *223*, 106997. [CrossRef]
46. Fimbres Weihs, G.A.; Jones, J.S.; Ho, M.; Malik, R.H.; Abbas, A.; Meka, W.; Fennell, P.; Wiley, D.E. Life Cycle Assessment of Co-Firing Coal and Wood Waste for Bio-Energy with Carbon Capture and Storage—New South Wales Study. *Energy Convers. Manag.* **2022**, *273*, 116406. [CrossRef]
47. Jha, S.; Nanda, S.; Acharya, B.; Dalai, A.K. A Review of Thermochemical Conversion of Waste Biomass to Biofuels. *Energies* **2022**, *15*, 6352. [CrossRef]
48. Ma, X.; Liu, F.; Helian, Y.; Li, C.; Wu, Z.; Li, H.; Chu, H.; Wang, Y.; Wang, Y.; Lu, W.; et al. Current Application of MOFs Based Heterogeneous Catalysts in Catalyzing Transesterification/Esterification for Biodiesel Production: A Review. *Energy Convers. Manag.* **2021**, *229*, 113760. [CrossRef]
49. Azimov, U.; Okoro, V.; Hernandez, H.H. Recent Progress and Trends in the Development of Microbial Biofuels from Solid Waste—A Review. *Energies* **2021**, *14*, 6011. [CrossRef]
50. Odega, C.A.; Ayodele, O.; Alagbe, O.; Adewole, A.; Adekunle, A. Review of Anerobic Digestion Process for Biogas Production. *Biosci. J.* **2022**, *10*, 81–96.
51. Lv, L.; Dai, L.; Du, W.; Liu, D. Progress in Enzymatic Biodiesel Production and Commercialization. *Processes* **2021**, *9*, 355. [CrossRef]
52. Scown, C.D.; Baral, N.R.; Yang, M.; Vora, N.; Huntington, T. Technoeconomic Analysis for Biofuels and Bioproducts. *Curr. Opin. Biotechnol.* **2021**, *67*, 58–64. [CrossRef]
53. Acharya, R.N.; Perez-Pena, R. Role of Comparative Advantage in Biofuel Policy Adoption in Latin America. *Sustainability* **2020**, *12*, 1411. [CrossRef]

54. Cherubin, M.R.; Carvalho, J.L.N.; Cerri, C.E.P.; Nogueira, L.A.H.; Souza, G.M.; Cantarella, H. Land Use and Management Effects on Sustainable Sugarcane-Derived Bioenergy. *Land* **2021**, *10*, 72. [CrossRef]
55. Kabeyi, M.J.B.; Olanrewaju, O.A. Biogas Production and Applications in the Sustainable Energy Transition. *J. Energy* **2022**, *2022*, 8750221. [CrossRef]
56. Jankovský, M.; García-Jácome, S.P.; Dvořák, J.; Nyarko, I.; Hájek, M.; Paletto, A.; Dobsinska, Z.; Carina, E.; Keskitalo, H. Innovations in Forest Bioeconomy: A Bibliometric Analysis. *Forests* **2021**, *12*, 1392. [CrossRef]
57. Sallustio, L.; Harfouche, A.L.; Salvati, L.; Marchetti, M.; Corona, P. Evaluating the Potential of Marginal Lands Available for Sustainable Cellulosic Biofuel Production in Italy. *Socioecon. Plann. Sci.* **2022**, *82*, 101309. [CrossRef]
58. Departamento Administrativo Nacional de Estadística-Instituto Colombiano Agropecuario. *National Livestock Census (Censo Nacional Agropecuario)*; DANE-ICA: Bogotá, Colombia, 2021.
59. Sagastume Gutiérrez, A.; Cabello Eras, J.J.; Hens, L.; Vandecasteele, C. The Energy Potential of Agriculture, Agroindustrial, Livestock, and Slaughterhouse Biomass Wastes through Direct Combustion and Anaerobic Digestion. The Case of Colombia. *J. Clean. Prod.* **2020**, *269*, 122317. [CrossRef]
60. TECSOL. *Estimation of the Biomass Potential for Conversion into Biogas in Colombia and Its Use (Estimación Del Potencial de Conversión a Biogás de La Biomasa En Colombia y Su Aprovechamiento)*; TECSOL: Bogotá, Colombia, 2018.
61. Rubén Rodríguez-Nuñez, J.; Surisadai, O.; Baltazar, C. Anaerobic Digestion Technology for Management of Organic Wastes: Latin American Context. In *Biogas Production*; Springer: Cham, Switzerland, 2020; pp. 39–55. [CrossRef]
62. Ahmed, N.; Qamar, S.; Jabeen, G.; Yan, Q.; Ahmad, M. Systematic Analysis of Factors Affecting Biogas Technology Acceptance: Insights from the Diffusion of Innovation. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102122. [CrossRef]
63. Abubakar, A.M. Biodigester and Feedstock Type: Characteristic, Selection, and Global Biogas Production. *J. Eng. Res. Sci.* **2022**, *1*, 170–187. [CrossRef]
64. Murugaiyan, J.; Narayanan, A.; Naina Mohamed, S. An Overview of Microbial Electrolysis Cell Configuration: Challenges and Prospects on Biohydrogen Production. *Int. J. Energy Res.* **2022**, *46*, 20811–20827. [CrossRef]
65. Tawalbeh, M.; Alarab, S.; Al-Othman, A.; Muhammad, R.; Javed, N. The Operating Parameters, Structural Composition, and Fuel Sustainability Aspects of PEM Fuel Cells: A Mini Review. *Fuels* **2022**, *3*, 449–474. [CrossRef]
66. Fadzli, F.S.; Bhawani, S.A.; Adam Mohammad, R.E. Microbial Fuel Cell: Recent Developments in Organic Substrate Use and Bacterial Electrode Interaction. *J. Chem.* **2021**, *2021*, 4570388. [CrossRef]
67. Sonawane, J.M.; Mahadevan, R.; Pandey, A.; Greener, J. Recent Progress in Microbial Fuel Cells Using Substrates from Diverse Sources. *Heliyon* **2022**, *8*, e12353. [CrossRef]
68. Ali, R.B.; Noori, M.T.; Lee, S.H.; Park, H.D.; Min, B. Enhancing Biogas and Electricity Recovery Using an Iron-Manganese Oxide Catalyzed Bioanode in an Integrated Submersible Microbial Fuel Cell-Anaerobic Digester. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102276. [CrossRef]
69. Guan, T.; Alvfors, P.; Lindbergh, G. Investigation of the Prospect of Energy Self-Sufficiency and Technical Performance of an Integrated PEMFC (Proton Exchange Membrane Fuel Cell), Dairy Farm and Biogas Plant System. *Appl. Energy* **2014**, *130*, 685–691. [CrossRef]
70. Chouhan, K.; Sinha, S.; Kumar, S.; Kumar, S. Steam Reforming of Biogas from Different Feedstocks for H_2 Production and Its Use in PEMFC: Thermodynamic Analysis. In *Water-Energy-Nexus in the Ecological Transition*; Springer: Cham, Switzerland, 2022; pp. 295–298. [CrossRef]
71. Ghorbani, B.; Mehrpooya, M.; Karimian Bahnamiri, F. An Integrated Structure of Bio-Methane/Bio-Methanol Cogeneration Composed of Biogas Upgrading Process and Alkaline Electrolysis Unit Coupled with Parabolic Trough Solar Collectors System. *Sustain. Energy Technol. Assess.* **2021**, *46*, 101304. [CrossRef]
72. Kong, F.; Swift, J.; Zhang, Q.; Fan, L.S.; Tong, A. Biogas to H_2 Conversion with CO_2 Capture Using Chemical Looping Technology: Process Simulation and Comparison to Conventional Reforming Processes. *Fuel* **2020**, *279*, 118479. [CrossRef]
73. Acevedo-Osorio, Á.; Chohan, J.K. Agroecology as Social Movement and Practice in Cabrera's Peasant Reserve Zone, Colombia. *Agroecol. Sustain. Food Syst.* **2019**, *44*, 331–351. [CrossRef]
74. Khan, N.; Ray, R.L.; Sargani, G.R.; Ihtisham, M.; Khayyam, M.; Ismail, S. Current Progress and Future Prospects of Agriculture Technology: Gateway to Sustainable Agriculture. *Sustainability* **2021**, *13*, 4883. [CrossRef]
75. Sarker, S.A.; Wang, S.; Adnan, K.M.M.; Sattar, M.N. Economic Feasibility and Determinants of Biogas Technology Adoption: Evidence from Bangladesh. *Renew. Sustain. Energy Rev.* **2020**, *123*, 109766. [CrossRef]
76. Iqbal, N.; Sakhani, M.A.; Khan, A.R.; Atiq-ur-Rehman; Ajmal, Z.; Khan, M.Z. Socioeconomic Impacts of Domestic Biogas Plants on Rural Households to Strengthen Energy Security. *Environ. Sci. Pollut. Res.* **2021**, *28*, 27446–27456. [CrossRef]
77. Tian, H.; Wang, X.; Lim, E.Y.; Lee, J.T.E.; Ee, A.W.L.; Zhang, J.; Tong, Y.W. Life Cycle Assessment of Food Waste to Energy and Resources: Centralized and Decentralized Anaerobic Digestion with Different Downstream Biogas Utilization. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111489. [CrossRef]
78. Ali, S.; Yan, Q.; Razzaq, A.; Khan, I.; Irfan, M. Modeling Factors of Biogas Technology Adoption: A Roadmap towards Environmental Sustainability and Green Revolution. *Environ. Sci. Pollut. Res.* **2022**, *30*, 11838–11860. [CrossRef]
79. Organisation for Economic Co-operation and Development. *Enabling Conditions for Bioenergy Finance and Investment in Colombia*; Green Finance and Investment; OECD: Bogotá, Colombia, 2021.

80. Alzate, S.; Restrepo-Cuestas, B.; Jaramillo-Duque, Á. Municipal Solid Waste as a Source of Electric Power Generation in Colombia: A Techno-Economic Evaluation under Different Scenarios. *Resources* **2019**, *8*, 51. [CrossRef]
81. Arias-Gaviria, J.; Carvajal-Quintero, S.X.; Arango-Aramburo, S. Understanding Dynamics and Policy for Renewable Energy Diffusion in Colombia. *Renew. Energy* **2019**, *139*, 1111–1119. [CrossRef]