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From Waste to Value: Key Insights and Lessons Learned from Biogas Initiatives in the Global South

Tosin Somorin, Susanne Bodach and Mansi Tripathi

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Tosin Somorin, Susanne Bodach and Mansi Tripathi

The authors

Tosin Somorin is Researcher - Circular Economy and Waste Management at the International Water Management Institute (IWMI), Accra, Ghana. She holds a PhD in Energy Engineering and has more than 10 years of experience in developing environmental solutions that enable circularity, net-zero carbon and zero-waste strategies.

Susanne Bodach is Research Group Leader - Integrated Circular Economy Transformations at IWMI, Colombo, Sri Lanka, and holds a PhD in Low-Carbon Development. With 20 years of work experience, her areas of interest include circular economy, sustainable energy, climate change and innovation scaling for overall agrifood system resilience.

Mansi Tripathi is Researcher – Resource Recovery and Reuse at IWMI, New Delhi, India. She holds a PhD in Environmental Management and has 8 years of experience in environment and sustainability with a focus on waste management, resource recovery and circular economy.

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Front cover photograph: Biogas Plant in Cochin, Kerala, India. *Photography by* Ponnu Sudheesh

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ACRONYMS AND ABBREVIATIONS

CH_4	Methane
CO_2	Carbon dioxide
GHGs	Greenhouse gases
HH	Household
LMICs	Low- and Middle-Income Countries
LPG	Liquefied Petroleum Gas
MCA	Multicriteria Analysis
MNRE	Ministry of New and Renewable Energy
NDBP	National Domestic Biogas Programme
OFMSW	Organic Fractions of Municipal Solid Waste
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental analysis
PNB-SN	Programme National de Biogaz Domestique du Sénégal
REA	Renewable Energy Act
RRR	Resource recovery and reuse
SNV	Netherlands Development Organization

SUMMARY

Wide-scale implementation of biogas technologies can significantly contribute to global climate mitigation efforts while also achieving renewable energy and waste management goals. However, many low- and middle-income countries have not been able to realize these benefits due to diverse sectoral challenges. This report explores the diverse barriers and challenges posed to large-scale biogas technology implementation, as well as the opportunities it brings, while recommending strategies for overcoming those obstacles. The key findings presented here highlight the importance of strong policy support, economic incentives, community engagement, technical reliability, and market development. The report emphasizes that overcoming these multifaceted challenges requires a coordinated approach that integrates policy reforms, financial mechanisms, public awareness campaigns, and robust supply chains to unlock the full potential of biogas as a sustainable energy solution and an important component of waste management strategies.

Some of the key lessons learned were:

1. Successful biogas programs tend to be those backed by strong government policies and incentives. Effective coordination and governance are essential for effective large-scale implementation.

2. Clarity of roles and responsibilities across governance levels is necessary, along with transparent market structures and financial incentives to encourage investment. Close collaboration between sectors and coordination among regulatory institutions are needed to minimize operational constraints, supply chain risks, and regulatory bottlenecks. Partnerships that promote knowledge sharing, best practices, and expertise exchange can enhance the adoption and efficient performance of these systems.

3. Streamlining decision-making and implementing long-term strategies for infrastructure, capacity building, and technological advancement are crucial.

4. The high upfront costs of infrastructure and maintenance are significant economic and market barriers. Access to finance is therefore critically important.

5. Public awareness and acceptance, both of which are processes laden with sociocultural and socioeconomic factors, significantly influence the uptake of biogas solutions. Addressing these challenges requires community engagement, targeted education, capacity-building, and awareness programs.

6. Local communities must be engaged early in the planning, decision-making, and implementation stages of biogas programs to enable them to understand the true costs and benefits.

7. Technical issues such as quality of construction, operational maintenance, and availability of spare parts can impede biogas adoption at scale. Standardization, local supplies, research and development, and provision of technical support are therefore necessary to achieve continuous operation and wider participation.

8. Developing well-functioning markets and robust supply chains is essential for the commercial viability of biogas technologies. Market-based instruments and financial mechanisms can support the growth of the biogas sector. Standardizing the industry and establishing clear guidelines can enhance market confidence in and attract private investment to biogas technologies.

9. Technological advances can further enhance the efficiency and adoption of biogas technologies. In these contexts, integrating resource recovery processes and obtaining multiple streams of energy and nutrients are essential for deriving comprehensive environmental, economic, and social benefits from biogas.

Commercialization of biogas technologies requires stable and growing market demand, which will ensure a consistent revenue stream, thereby attracting funding for project development. Special attention needs to be given to problems and challenges that are unique to specific countries, and solutions should be customized based on the local needs and available resources. Implementing these recommendations could facilitate wide-scale implementation of biogas technologies while maximizing the circular economy principle.

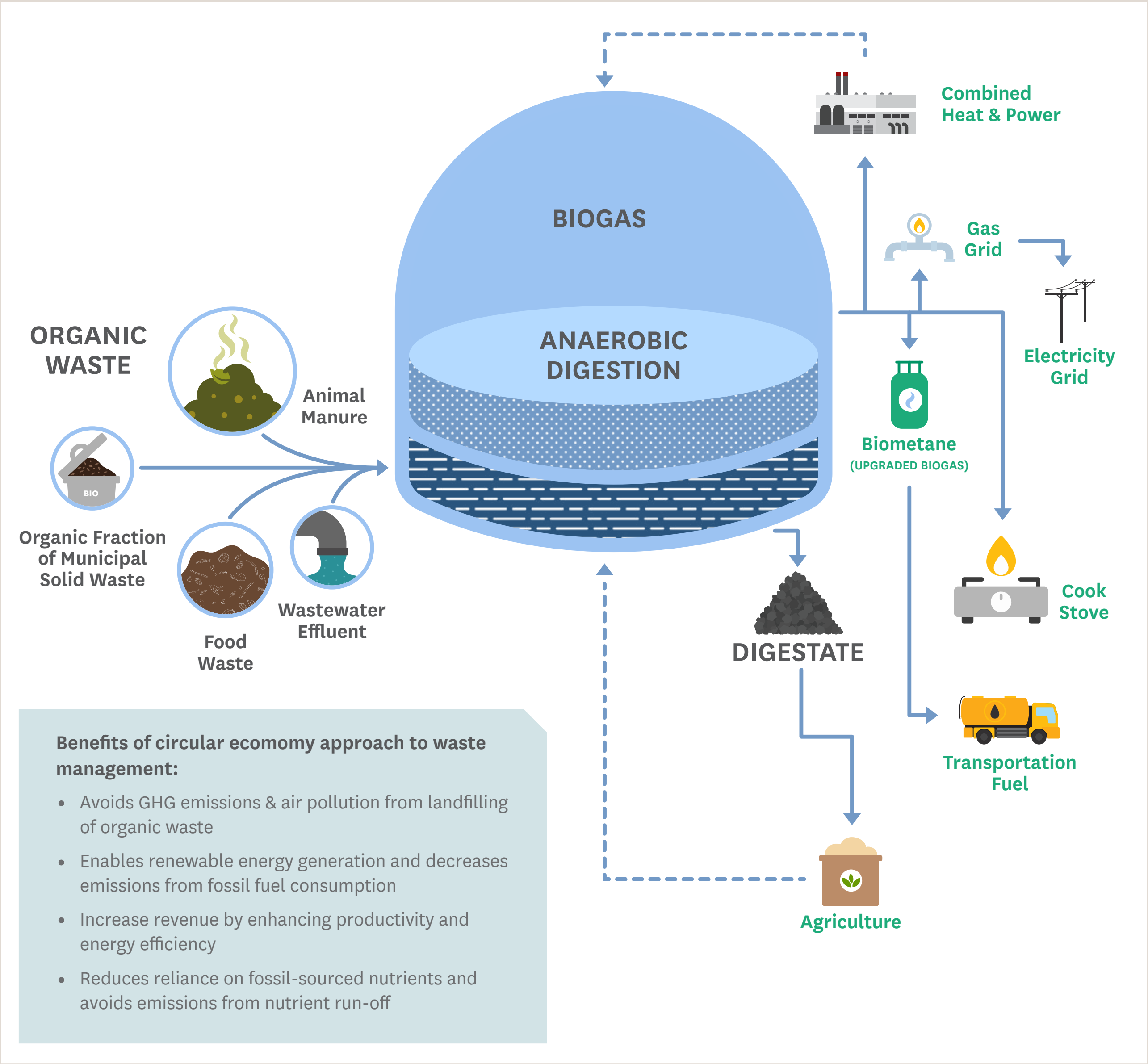
1

INTRODUCTION

Biogas plant - Westeregeln near Magdeburg, Deutschland.
Photography by René

Global warming is undoubtedly one of the major environmental challenges that the world faces today. Its impact on climate encompasses rising average temperatures, extreme weather events, changes in rainfall patterns, rising sea levels, and a variety of other consequences (van Aalst 2006). These effects are expected to intensify as anthropogenic pressures heighten and emissions of heat-trapping greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) are added to the atmosphere. The Paris Agreement, adopted in 2015 at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, aims to limit global average temperature to well below 2°C above preindustrial levels by 2050 (Falkner 2016) through a multipronged response, which includes national commitments to reduce GHG emissions. One of the targeted approaches to cut down GHGs involves capturing carbon emissions via anaerobic digestion, which converts emissions that would otherwise be released during organic matter decomposition to produce biogas and a residual digestate as a by-product (Baştabak and Koçar 2020).

Biogas is mainly a mixture of CO_2 and CH_4, although other gases like hydrogen sulfide can be present. It is a versatile fuel that can be used, for example, in boilers and power plants to produce heat and/or electricity. It can be used directly in a gas stove for cooking, or as a low-carbon fuel in vehicles (Angelidaki et al. 2003; Gray et al. 2021). Enhanced biogas (free of CO_2 and other impurities) can be conveniently stored as compressed or liquefied biomethane or injected directly into existing national gas grids (Kapoor et al. 2020). This makes biogas a versatile energy vector, particularly for consumers who are off the grid, and as a convenient energy source of power (Rafiee et al. 2021). On the other hand, the digestate, which is a mixture of water, nutrients, and organic carbon, can be applied to agricultural land, composted or separated into liquid and solid fractions before application to soil (Kovačić et al. 2022). Liquid effluents can be integrated into a biorefinery to produce high-value bioproducts, including nutrients and bioplastics (Malhotra et al. 2022). This resource recovery and reuse (RRR) approach of converting organic waste into value-added biogas and digestate is transforming linear food systems, particularly in the aspects of renewable energy generation and nutrient recycling. Figure 1 illustrates how anaerobic digestion contributes toward a circular bioeconomy. Box 1 describes a typical biogas plant system configuration set in a variety of contexts.



Benefits of circular ecomomy approach to waste management:

- Avoids GHG emissions & air pollution from landfilling of organic waste
- Enables renewable energy generation and decreases emissions from fossil fuel consumption
- Increase revenue by enhancing productivity and energy efficiency
- Reduces reliance on fossil-sourced nutrients and avoids emissions from nutrient run-off

FIGURE 1. Anaerobic digestion of organic waste as part of a circular bioeconomy.

Source: Authors.

Box 1: Biogas plant explained.

A biogas plant, also known as an anaerobic digestion facility, creates an oxygen-free environment for microorganisms present in the waste to convert organic matter into usable energy and nutrient-rich media. A typical digester (Figure 2) is an air-tight and waterproof container with the following components: (i) an inlet through which organic waste is fed into the system in slurry form; (ii) a fermentation chamber in which microorganisms act upon the waste to produce biogas; (iii) an exit pipe for biogas removal; (iv) a storage tank to capture and store the gas for later use; (v) an outlet for slurry outflow and recovery; and (vi) an overflow tank to collect the excess effluent.

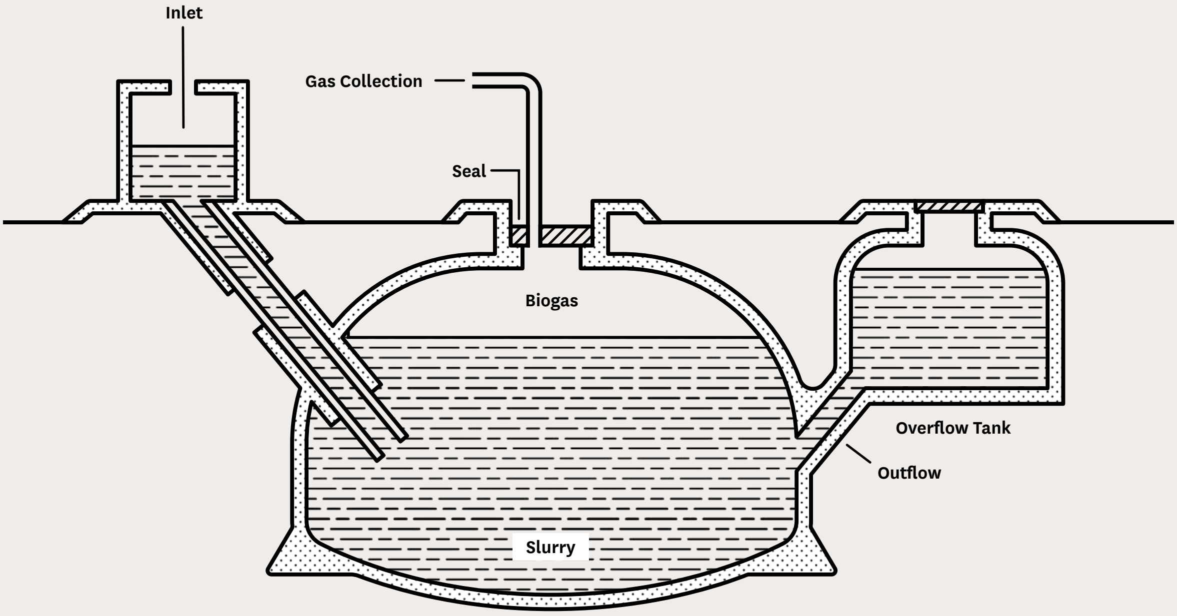


FIGURE 2. Schematic diagram of a fixed-dome biogas plant.

Source: Halder et al. 2016.

There are various kinds of digesters, often classified by size: small, household-scale digesters (below 20 m^3) are primarily used for domestic cooking and heating; medium digesters (up to 1,000 m^3) are tailored for institutional, communal, or farm-level operation; and large-scale industrial biogas plants are used for commercial operation (4,000 m^3 and above). There are an estimated 50 million microscale digesters (0.2 to 100 m^3 in size) operating across the world; 90 percent of these are in China and the rest are sparsely distributed in other parts of the world (WBA 2019; 2021). Various digester designs, such as fixed-dome, floating-drum, balloon, horizontal, earth-pit, and ferrocement plants, can be found worldwide, serving both large- and small-scale purposes. Depending on the design, feedstock, and size of the digester, a variety of automation can be achieved using mechanical, hydraulic, pneumatic, or passive systems, e.g., for mixing, sampling, and monitoring (Issahaku et al. 2024). Making the right decisions on the size and type of digester, materials for construction, feedstock type, safety considerations, and economic viability is critical for the success of a biogas plant.

1.1. Biogas Technology as an Environmental Solution

The approach of recovering biogas and nutrients from organic waste makes biogas technology a key environmental solution. It can reduce the uncontrolled release of CH_4 emissions by diverting degradable waste from landfills, ease global dependence on non-renewable fuels, and diversify energy sources, thereby protecting the environment. By incorporating biogas technology into national climate action plans and implementing it on a large scale, countries can contribute to the global effort to combat climate change while also achieving broader policy objectives relating to renewable energy and agricultural and urban waste management. Besides, transitioning to an organic waste-based biogas energy source provides ample opportunity to increase the energy security of the rural sector and accelerate rural development by increasing revenue generation, creating more eco-friendly jobs, improving soil productivity, and facilitating greater freedom for girls and women. These socioeconomic benefits can be achieved if safer and sustainable biogas alternatives replace traditional biomass-based cooking practices; digestate replaces costly fossil-based synthetic fertilizer; organic wastes are prevented from entering waterways; and nutrients are circulated in nature.

Despite this broad range of benefits, wide dissemination of biogas plants is still limited globally. According to the 2019 Global Potential of Biogas report by the World Biogas Association, only 2 percent of the world's total biogas potential is being realized. Even in countries where there has been large dissemination of biogas plants, as in China, a look at the potential for production and installed capacities indicates a wide gap (WBA 2019). For example, in 2017, China produced at most 300 petajoules (PJ) of biogas compared to its production potential of 13,275 PJ per year (Yuan and Gerbens-Leenes 2021). In many parts of the global south, micro-digesters are primarily used for producing biogas for cooking, which underutilizes the vast environmental and socioeconomic benefits that RRR strategies can bring to waste management and climate change mitigation. In countries like Nepal, India, and Rwanda, national biogas or support programs have been implemented and are reportedly successful (Katuwal and Bohara 2009; Rupf et al. 2015; Patinvoh and Taherzadeh 2019), leading to a large rollout of domestic, small-scale biogas technologies but only a limited number of medium- and large-scale plants. In other countries, for example in Uganda and Tanzania, such programs have not fully yielded the anticipated outcomes. Where pilot/demonstration projects have been implemented, they have been reported to fail, in some cases leading to technology abandonment or disengagement (Namugenyi et al. 2022; Hewitt et al. 2022). There is a need to understand why biogas sector development has been rapid in some countries but not in others; and why some plants are economically viable while others have failed or lagged despite government support. Understanding these underlying barriers, their root causes, and their impacts is the prime objective of this report. Such insights can enable the development of effective strategies to overcome these constraints.

A few studies have investigated the drivers of and barriers to the diffusion of biogas technologies, exploring country-level factors, institutional arrangements, and user perspectives (Kamp and Bermúdez Forn 2016; Björner Brauer and Khan 2021; Hasan et al. 2022; Hewitt et al. 2022). However, most of the case studies on large-scale biogas plants are from a handful of countries like China (Zhang and Xu 2020; Xue et al. 2020), Germany (Wilkinson 2011), Denmark (Raven and Gregersen 2007; Lybæk et al. 2014; Nielsen 2022), and Sweden (Niskanen and Magnusson 2021), where centralized, large-scale biogas plants are prominent in power generation and farm waste management. In low- and middle-income countries (LMICs), except China, there has been limited progress on wide-scale implementation of medium- to large-scale biogas plants, particularly for urban waste management. A few studies that investigated or analyzed the factors influencing biogas sector development in LMICs have tended to focus on household digesters (Rupf et al. 2015; Yin et al. 2017; Hasan et al. 2022; Tavera-Ruiz et al. 2023), citing techno-economic considerations such as lack of feedstock supply, operational challenges, and lack of finance and skilled workers as major barriers to wide-scale adoption. The underlying socioeconomic and cultural factors, as well as the policy environment influencing this sector, have been sparsely examined. Aiming to fill this gap, this present review explores different country contexts within LMICs to draw insights and lessons from various biogas programs, initiatives, and project reviews, and to analyze the barriers to and opportunities for the wide-scale implementation of biogas technologies. The emphasis in this report is on biogas plants designed for urban effluent treatment, large livestock farming, and community-scale processing of organic waste rather than domestic, household digesters.

2

METHODOLOGY

This study adopted a combination of approaches to comprehensively identify and categorize the different macroenvironmental and contextual factors that affect large-scale biogas implementation. First, a scoping review was conducted to identify, assess, and synthesize interrelated ideas and the current understanding of macroenvironmental factors influencing wide-scale biogas implementation in LMICs. This was achieved by (i) developing a guiding framework for a scoping review of literature; (ii) formulating a set of research questions; (iii) identifying key data sources and developing a search strategy; (iv) formulating a set of exclusion and inclusion criteria for data screening; and, finally, (v) data extraction and synthesis. More details of this approach are presented in sections 2.1 to 2.4.

The studies identified in the scoping review described above were analyzed using seven multidimensional criteria identified by Otoo et al. (2016) for assessing the feasibility of RRR business models. This multicriteria analysis (MCA) covered aspects of technical and logistical assessment; waste supply and availability; health and environmental risk and impact assessment; institutions, regulations, and investment climate; socioeconomic and cultural assessment; financial analysis; and market assessment. Furthermore, the various macroenvironmental factors identified in the scoping study were categorized into six dimensions using PESTLE (political, economic, social, technological, legal, and environmental) analysis method, which provides valuable insights into the possible outcomes that may result in success or failure of biogas projects. This analytical framework is widely used in management studies and renewable energy projects for identifying issues that may significantly impact the future of a project, an industry, or a market (Sridhar et al. 2016; Achinas et al. 2019). In this study, the term 'political factors' refers to the role of government in influencing an industry or market and explores several aspects of government policies. Economic factors consider the financial and economic environment, including the effects of inflation, interest rates, and foreign direct investment. Social factors explore dimensions of cultural norms and expectations, public awareness, education, and bias toward technologies. Technological and technical factors pertain to innovations in technology that can impact industry operations and the market, such as design and technological awareness. Legal factors consider the impact of national and international legislation, taxation, and regulations. Environmental factors encompass everything determined by the environment, including climate, geographical location, pollution prevention, and national and local environmental issues including organizational and community attitudes toward the environment. All these aspects considered together give a comprehensive overview of the opportunities and challenges present in the biogas sector. Table 1 summarizes the interdependencies between the PESTLE framework and the RRR multicriteria factors.

TABLE 1 . Interdependencies between PESTLE and RRR multicriteria factors.

Multicriteria dimensions	Political	Economic	Social	Technical	Legal	Environmental
Technical and logistical assessment	x	x	x	x		x
Waste supply and availability	x	x	x	x		x
Health and environmental risk and impact assessment		x	x			x
Institutions, regulations, and investment climate	x				x	x
Socioeconomic and cultural assessment			x	x		x
Financial analysis	x	x		x		
Market assessment		x	x	x		

2.1. Guiding Framework and Research Questions

The guiding framework for this study, presented in Figure 3, assumes that wide-scale deployment of biogas plants and establishment of biogas programs in LMICs are hindered by several factors, with independent variables that can be identified, categorized, and analyzed in their political, economic, sociocultural, technical, legal, and environmental aspects. It also assumes that biogas plants are implemented for resource recovery purposes (e.g., energy and/or nutrient recovery), whether formally recognized or not. Biogas technology is used in the context of systems designed to turn organic waste into usable energy and digestate as a by-product. Table 2 outlines the key research questions applied for the multidimensional scoping review of literature, building on the MCA methodology described in Otoo et al. (2016) and the PESTLE framework shown above.

2.2. Data Sources and Search Strategy

The search queries were based on key components of the research objectives and questions such as ‘biogas’, ‘lessons learned’, and ‘LMICs’. The term ‘biogas’ was included in all search queries to capture the context in which the technology is being used, but ‘anaerobic digestion’ was also applied to cover the breadth of use. As this report focuses on the lessons learned, keywords such as ‘drivers’, ‘success’, ‘accelerators’, ‘enablers’, ‘opportunities’, ‘potentials’, and ‘driving forces’ were included in the search query to capture positive influences and different forms of use. Terms such as ‘failure’, ‘barriers’, ‘constraints’, ‘impediments’, ‘inhibitors’, ‘risks’, ‘threats’, ‘challenges’, ‘obstacles’, ‘obstructions’, and ‘limitations’ were also included to capture the negative influences on technology scaling and wide-scale adoption. Additional terms included were ‘lessons learned’, ‘lessons learnt’, and ‘best practices’, which are often used in associated literature.

Three databases were searched, JSTOR, Web of Science, and Scopus, as well as Google Scholar and gray papers, using a ‘snowballing’ approach.

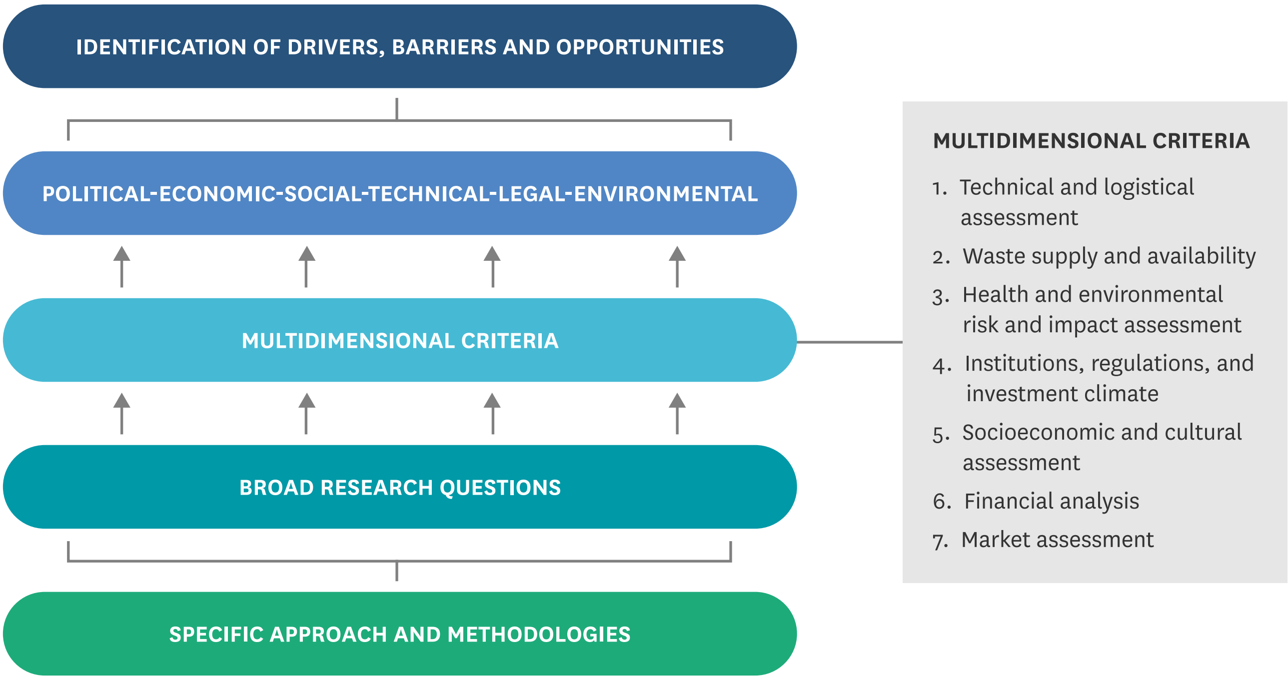


FIGURE 3. Guiding framework for identifying drivers, barriers, and opportunities.

Source: Modified from Otoo et al. 2016.

TABLE 2. Broad research questions for the review of literature.

Technical and logistical assessment	What biogas technologies are being implemented in LMICs, and for what purpose? What are the associated capital and operational costs at various scales? What technical drivers and barriers hinder wide-scale biogas implementation? How do technology design, operational performance, repair, maintenance, labor, and technical capacity of operators influence technology adoption? What enabling environmental factors are needed to ensure viable plant operation and economics?
Waste supply and availability	What types of waste are processed? Are there supply limitations of resource input? How do feedstock supply, periodicity, and seasonality affect technical, economic and environmental performance of biogas plants?
Health and environmental risk and impact assessment	What environment-related drivers and barriers influence wide-scale biogas implementation? What are the quantifiable environmental costs and benefits of biogas technologies, including averted GHG emissions and cost savings? What are the unintended environmental risks associated with biogas technology? What kind of capacity development, incentive systems, and monitoring strategies are needed to ensure compliance in the local context?
Institutional and regulatory assessment	What policies, regulations, and by-laws promote medium-to-large-scale biogas projects? Are there any incentives/disincentives in place? Is the institutional framework supportive of project development and implementation? To what extent does the enabling environment attract private investment?
Socioeconomic assessment	What sociological barriers limit wide-scale biogas implementation and are responsible for project failures? How do demographics influence the willingness of households to pay for biogas technology? How do socioeconomic and geographical factors hinder or enable adoption?
Financial analysis	What financial barriers limit the adoption of biogas in developing countries? Are biogas plants financially viable, and, if so, under what conditions? What incentives (gains, savings, subsidies, fiscal support) encourage different actor participation for a win-win situation along the RRR value chain?
Market assessment	What barriers limit the market entry of biogas technologies and products in developing countries? Are there any sociocultural aspects and perceptions that impact household willingness to pay for biogas technology? What negative perceptions discourage households from uptake of biogas technology?

Source: Authors.

2.3. Data Screening

Our criteria for inclusion and exclusion of data considered the geographical context, research landscape, language, period of publication, type of article, and reputation of the journal. Given that the scope of the study encompassed medium- to large-scale biogas plants—that is, those systems operated on large farms, at a community scale, or for commercial production of electricity and heat—it was important to exclude literature focused on rural and household biogas digesters. To achieve this, the term 'comm*' was separately included in the search term to capture specific reports on commercial, community-scale, and communal biogas plants. Literature that solely focused on laboratory/experimental investigation and process modeling was excluded. Peer-reviewed journal articles, those published in SCI and/or Ei Compendex journals, were included, but book chapters and conference papers were excluded. Only papers published and available in English were included. Final selection for study was done by screening the title and abstract and, in some cases, the full text.

2.4. Data Extraction and Analysis

This report draws out insights and lessons from biogas initiatives to arrive at a holistic understanding of the macroenvironment in which these technologies operate and the influence of contextual factors in constraining or accelerating large-scale biogas implementation. In Chapter 3, a few case studies are presented to illustrate the drivers of diffusion and implementation of biogas technologies in the global south, expanding on country- and context-specific factors enabling wide-scale implementation and their impact on technology aggregation. Chapter 4 outlines the major barriers, while exploring the PESTLE dimensions, to deployment, implementation, and adoption of biogas technologies. This multi-region and country approach, as well as the consideration of different dimensions of biogas development at scale, explored from political, technical, financial, and institutional aspects, facilitates a multifaceted understanding of the complex issues faced by biogas development in LMIC contexts. Chapter 5 highlights the lessons to be learned from the reported experience and makes sector-wide policy recommendations for effective large-scale biogas sector development in LMICs. This includes a discussion on the enabling environment that is needed to achieve successful outcomes as well as meet the diverse and multiple objectives of national biogas and biogas support programs and climate action efforts. These findings can be used by decision-makers to develop effective national and subnational policies and multisectoral interventions needed for biogas program design, implementation, and scaling.

A woman farmer spreading nutrient-rich slurry in her field. Slurry is a by product obtained from a household biogas plant at Akole, Maharashtra, India.
Photography by BAIF, India

3

DRIVERS OF BIOGAS TECHNOLOGIES IN THE GLOBAL SOUTH

The mass dissemination of small-scale biogas digesters seen in the Asia-Pacific region and Sub-Saharan Africa is largely driven by National Biogas Programs backed by government guarantees, loans, grants, subsidies, and incentives, often combined with funding from international donors or development banks (Rupf et al. 2015; Patinvoh and Taherzadeh 2019). This section uses a few case studies from these regions to illustrate the drivers of diffusion and wide-scale implementation of biogas technologies in the global south, taking note of the country-specific factors enabling large-scale implementation and their impact on technology aggregation.

3.1. China Biogas Program

The national biogas program in China encompasses various forms, ranging from traditional digesters used to produce biogas for cooking and heating to more modern energy systems designed for large-scale production of heat, electricity, and vehicular fuel (Table 3). Biogas technology was introduced in China in the early 1920s but was not formally recognized and effectively diffused until the 1970s when the government began rolling out biogas plants to address energy shortages and reduce dependence on firewood in rural areas (Song et al. 2014). From the 1970s through to the 1990s, several types of digesters—hydraulic cylinder type, separated floating bell type, and prefabricated block digesters—were promoted and installed in great numbers, but the sector suffered setbacks due to construction quality and gas leakage issues. Household biogas expansion stalled as a result. In the 1990s, new regulations, standards, policies, and implementing organizations were brought in with an emphasis on the quality of construction and management. From the 2000s, the sector started transitioning to sizeable biogas plants, including community biogas facilities and industrial-scale digesters for household use and larger agricultural and industrial applications respectively. Since then, the biogas industry has rapidly evolved. At the end of 2018, over 39 million household digesters were in operation, and the biogas program reached around 100 million people, supplying digesters to a quarter of the rural households (Aamodt and Chen 2013). Every year, an estimated 1 million digesters are being added under the influence of a range of economic, environmental, social, and policy-related factors (Song et al. 2014; WBA 2021).

The drivers of technology diffusion and implementation include (i) enabling policies and support for renewable energy projects in rural areas; (ii) various funding mechanisms, including capital subsidies, tax rebates, bonds, loans, and in some cases, grants for constructing and demonstrating biogas plant projects (subsidies, for instance, increased from renminbi (CNY) 0.1 billion in 2001 to CNY 3 billion in 2008); and (iii) standardization in the industry with 33 specifications issued between 2005 and 2011 (Wang et al. 2020).

TABLE 3. Biogas development in China.

Time period	Biogas activities
1880–1900s	Simple biogas digesters demonstrated.
1921–1942	Luo Guorui of Taiwan invented the ‘hydraulic pressure biogas pool’ and established the Guorui Gas Lamp Company, which led to the expansion of biogas production to 13 provinces.
1958–1970	The National Biogas Construction Leading Group was set up to address construction and installation issues, leading to mass development of digesters. Specialized biogas research institutions were established to address sectoral challenges.
1970–1990	The Chinese Biogas Association was founded in the third stage of biogas technology implementation. Household digester installations increased from 100,000 to 500,000 per year. Policies were made for uniform construction and operation of biogas plants with emphasis on quality of construction and management, practical results, and steady development. A national intervention was launched to repair or reinstall previously built digesters.
2001–2006	Various campaigns were established to expand biogas technology from Southern to Northern provinces, enabled by the 11th Five-Year Plan for National Economic and Social Development (2006-2010), and the 12th Five-Year Plan for Renewable Energy Development (2011–2015). Funding mechanisms were created for rural biogas development.
2007–2014	A series of policies, regulations, and laws were launched to promote proper management of biogas digesters. Concerted efforts were made by various ministries to consolidate prior work by increasing the speed of construction and strengthening quality control.
2015–2022	Subsidies for household biogas digesters were suspended in 2015. There was a gradual decrease in smallholder farming and concurrently an expansion of large-scale farms, which led to greater implementation of medium- to large-scale biogas plants.

Sources: Song et al. 2014; Wang et al. 2020.

3.2. Nepal Biogas Program

In Nepal, the first official biogas program was launched in 1974, but initial progress was slow (Table 4). A state-owned company was set up to promote the wide-scale dissemination of biogas technology but the installation rate between 1977 and 1990 remained limited. The technical potential of the country was estimated at 1.5 million units and the target for installation was set at 4,000 units per year. However, the average installation was only about 800 units per year by 1985. It rose to no more than 6,000 units in 1990. The slow implementation was attributed to high installation costs, frequent repairs due to poor quality of materials and installation, scarcity of supply infrastructure and networks, and inconsistent subsidies and assistance. To promote biogas use, the government initially increased subsidies from 25 percent to 50 percent and provided additional support for interest and loan repayment; however, all forms of subsidy were stopped in 1990. This halted the progress of biogas implementation (Bajgain and Shakya 2005). In 1992, a Biogas Support Program was initiated and co-funded by the Government of the Netherlands. Its aims were to provide technical assistance, promote wide-scale use of biogas by rural households, and encourage sector privatization. This program implemented a wide range of technical assistance and support activities, including active training of technicians and personnel, setting up monitoring and inspection mechanisms, and providing extension services. The number of installations increased to 49,000 units between 1992 and 1998, and more than 200,000 members of rural households benefited from the program. Chinese and Indian fixed-dome digester models with capacities ranging from 4 m^3 to 20 m^3 were promoted because they can be constructed with locally available materials like clay, brick, cement, and bamboo (Gautam et al. 2009). The biogas sector in Nepal has made remarkable progress since then, with 220,000–260,000 installations in 75 districts between 2010 and 2011, benefiting 1.3 million people (Rupf et al. 2015; Rai and Shrestha 2012). The drivers of this spurt in technology diffusion include creative market development in competitive conditions; private-sector participation; financial support mechanisms including structured loan and subsidy programs for poor and disadvantaged persons; institution strengthening and new regulations on quality and service standards; formation of coalitions and biogas promotion groups for grassroots engagement and increasing awareness in the rural population. These drivers also reduced the overall cost of biogas plants by more than 30 percent and supported small and medium-scale rural farmers in installing digesters (Rai and Shrestha 2012).

TABLE 4. Biogas development in Nepal.

Year	Biogas-related activity
1955	First demonstration model
1974	Biogas program initiated to promote construction of 250 biogas plants with interest-free loans.
1977	State-owned Biogas and Agriculture Equipment Development Pvt. Ltd. (also known as Gobar Gas Company) established.
1980	Gobar Gas Company (GGC) modified the Chinese fixed-dome model.
1990	GGC-modified fixed-dome model accepted as a suitable model for Nepal.
1991	Biogas Support Program established to oversee Nepal's biogas sector.
1991 onward	Approximately, 140,000 biogas plants installed all over the country. Numerous private-sector businesses enter the market. Microcredit financing becomes popular.

Source: Gautam et al. 2009.

3.3. India Biogas Program

India’s first national biogas program, the National Project on Biogas Development, was started in 1981 to promote biogas technologies to meet household cooking and lighting needs using cattle dung and other biowaste. In 2005, the initiative was expanded and renamed as the National Biogas and Manure Management Programme, incorporating other government rural schemes, including manure management. It promoted digesters of 1-6 m^3 capacity and off-grid, decentralized renewable generation of 3 kW to 250 kW of power. This program also set out to address sectoral issues relating to poor installation and quality of construction and materials, reporting and accounting of project outcomes, including double-counting and overreporting of achievements, and lack of accountability for failure/nonfunctionality (Raha et al. 2014). In 2018, the Ministry of New and Renewable (MNRE) established the New National Biogas and Organic Manure Programme to promote specific digesters with installed capacities of 1-25 m^3/day with emphasis not only on producing cooking fuel but also organic fertilizer. The program also promoted the development of community-scale biogas plants with installed capacities of 30m^3/day to 2,500 m^3/day. It supported such initiatives with funding, providing 30-35 percent of the project cost in the form of subsidies. These measures served to expand biogas development in India at various scales.

Recent reports show that India has over 5 million small-scale biogas plants and approximately 70,000 m3/day of community-scale digesters across the country spanning different biogas programs (Aggarwal et al. 2021; MNRE 2023). Other mechanisms enabling biogas development include the Sustainable Alternative Towards Affordable Transportation initiative developed by the Ministry of

Farmers undergoing training O&M of household biogas unit at BAIF-CRS campus, Urlikanchan, Maharashtra, India
Photography by BAIF, India

Petroleum and Natural Gas to promote compressed biogas production; and the Galvanizing Organic Bio-Agro Resources Dhan initiative by the Department of Drinking Water and Sanitation designed to improve sanitation. For the latter initiative, MNRE provides up to 100 percent of the project cost, depending on the scale of the project. Various other waste-to-energy projects have been initiated across the country to promote the use of urban, industrial, and agricultural wastes, either for captive energy needs or direct injection into the grid. Installed capacities were estimated at 702,508 m^3/day of biogas, 84,759 kg/day of compressed biogas, and 141 MW of biogas-based power. The MNRE provides financial incentives in the form of capital subsidies to project developers and state agency funding for promotion, training, and outreach (MNRE 2023). Funding was also provided to research institutions and subsidies were given to the private sector for demonstration projects. Biogas Development and Training Centres were instituted to offer technical assistance and carry out on-site inspections and monitoring (Aggarwal et al. 2021).

3.4. Rwanda Biogas Program

Coming out of its civil war, Rwanda had limited access to electricity. So, its people used biomass (wood and charcoal), mainly from *Eucalyptus* plantations, to meet their domestic energy needs, including cooking and lighting. The use of gas and electricity for cooking was negligible in both rural and urban areas (Bedi et al. 2015). To address this energy crisis and the resulting economic and environmental challenges, the Rwandan government established the National Domestic Biogas Programme (NDBP) in partnership with the Netherlands Development Organization (SNV) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in 2007 (Owekisa 2008). The target group for the program was rural households owning cattle. The initial target of the program was to install 15,000 digesters by the end of 2011, but it was reduced to 5,000 in 2009, and 3,000 in 2010. By 2012, only 2,447 digesters had been built (Kabera et al. 2016). Due to the limited uptake, Energising Development (EnDev) Rwanda, an international flagship program for providing energy access coordinated by GIZ and SNV, ended support for the program in 2011, but NDBP was continued by the Rwandan government through its Energy Development Corporation under the Rwandan Ministry of Infrastructure. In 2015, NDBP was decentralized to the 30 administrative districts of Rwanda to lead the implementation (Landi et al. 2013).

The major factors that limited the uptake of digesters in Rwanda were the high initial costs of obtaining a digester and the low benefits, which were below estimates. The actual cost of a 6 m^3 digester was three times the estimate. The smallest digester (4 m^3) cost about 1.4 times the average annual expenditure of rural households and the subsidy of RWF (Rwandan franc) 300,000 per household was insufficient. Also, since households had to pay for water (used to make the cow dung slurry for the digesters), it added to the operating cost of the digester. While NDBP offered loans through a bank, the conditions for accessing the loan were stringent. Furthermore, there were few field technicians available to construct, service, and repair digesters. A study showed that 43 percent of the households surveyed had biodigesters that were nonfunctional (Kabera et al. 2016), mainly due to poor workmanship or limited technical capacity.

These challenges became more evident after implementation of the NDBP was decentralized to the districts. While the intention had been to bring biogas construction and maintenance services closer to the end-users (Anaclet 2023), the unintended consequence was that technicians were not sufficiently skilled to handle technical issues and maintenance. Despite these challenges, multistakeholder partnerships with local organizations and NGOs such as World Vision Rwanda and SNV did enhance the uptake of digesters in Rwanda. For example, the United Nations Development Programme in Rwanda partnered with an Israel-based company and the government of Eastern Province to provide 500 households in Rwamagana and Ngoma districts with new digester models such as movable aerobic digesters to help reduce the cost (Tushabe 2023). The NDBP's effort has led to a 31–32 percent reduction in household expenditure on energy and a 34 percent reduction in the use of firewood for energy in Rwandan households (Bedi et al. 2015).

3.5. Senegal Biogas Program

In Senegal, firewood is the primary source of energy for households, followed by charcoal and liquefied petroleum gas (LPG). While about 70 percent of urban households (90 percent in Dakar, the capital city) use LPG for cooking, rural areas rely on biomass, consuming over 1.7 million tons (Diouf and Miezan 2019). Thus, the main aim of Senegal's national domestic biogas program, named Programme National de Biogaz Domestique du Sénégal (PNB-SN), was to offer a better alternative cooking fuel to people living in farming areas. The PNB-SN program set out to install 8,000 household digesters between 2009 and 2013 but managed to set up less than 600 digesters, of which 30 percent subsequently became nonfunctional. So, farmers went back to using firewood for cooking. The failure of the PNB-SN was technically attributed to the inability of human resources to construct and maintain the biodigesters. Phase 1 of the program did not consider the structural poverty of end-users and the limited technical competencies available to service the biodigesters.

Phase 2 of the PNB-SN program was launched in 2015 with the support of the European Union and the World Bank. The target was raised to 10,000 digesters. The main challenge faced by the program was the high cost of installing biodigesters in rural households. The cost of installing a 10 m^3 biodigester was about 70 percent of the average annual income of households, going as high as 105 percent in some areas. Further, high interest rates (12-24 percent) and difficulties in accessing loans due to a lack of savings or guarantees ensured that the acceptance rate of biodigesters remained low in rural areas. The government subsidy of USD 270 was insufficient to encourage farmers to purchase biodigesters.

To overcome these challenges, a new initiative was launched to double the number of digesters in rural households through an innovative financing structure. This program enables easier access to credit for biogas enterprises to install biodigesters for preselected end-users who will benefit from clean cooking systems while generating an income by selling biofertilizers.

The analysis of various national biogas programs presented in this section shows that the underlying drivers of biogas technology diffusion differ, ranging from policies, legal and regulatory frameworks to sector reforms, financial instruments, and technical assistance. The objectives of setting up national biogas or biogas support programs are broadly similar in different countries and regions. These could be to (i) increase the use of renewable energy resources and diversify the energy mix; (ii) improve energy access in rural areas and expand rural electrification; (iii) forge low-carbon development pathways for power generation and agriculture (e.g., the use of organic fertilizer instead of chemical fertilizers, and alternative fuels); (iv) reduce rural communities' dependency on traditional fuels like charcoal and firewood or fossil fuels like LPG and kerosene; (v) end open defecation and improve modern sanitation; (vi) expand rural development through poverty alleviation, farmer income diversification, and improved agricultural productivity; and (vii) promote climate change mitigation and adaptation.

Some of the macroenvironmental mechanisms that have enabled biogas technologies to be diffused across regions, irrespective of scale, are access to technical assistance and institutional support for research and development, and quality and service standards (Song et al. 2014; Wang et al. 2020; Aggarwal et al. 2021); access to various financial instruments and support mechanisms for development and implementation of biogas projects (Thrän et al. 2020); positive acceptance of biogas technologies (Rupf et al. 2015; Clemens et al. 2018); an enabling policy environment for biogas projects with targeted support for rural development (Song et al. 2014; Thrän et al. 2020; Tavera-Ruiz et al. 2023); and a well-established biogas market with competitive conditions (Clemens et al. 2018). However, further analysis shows that many countries have not realized the benefits of large-scale implementation of biogas technologies due to diverse sectoral challenges. Figure 4 summarizes the various underlying drivers and environments enabling biogas technologies in LMICs.

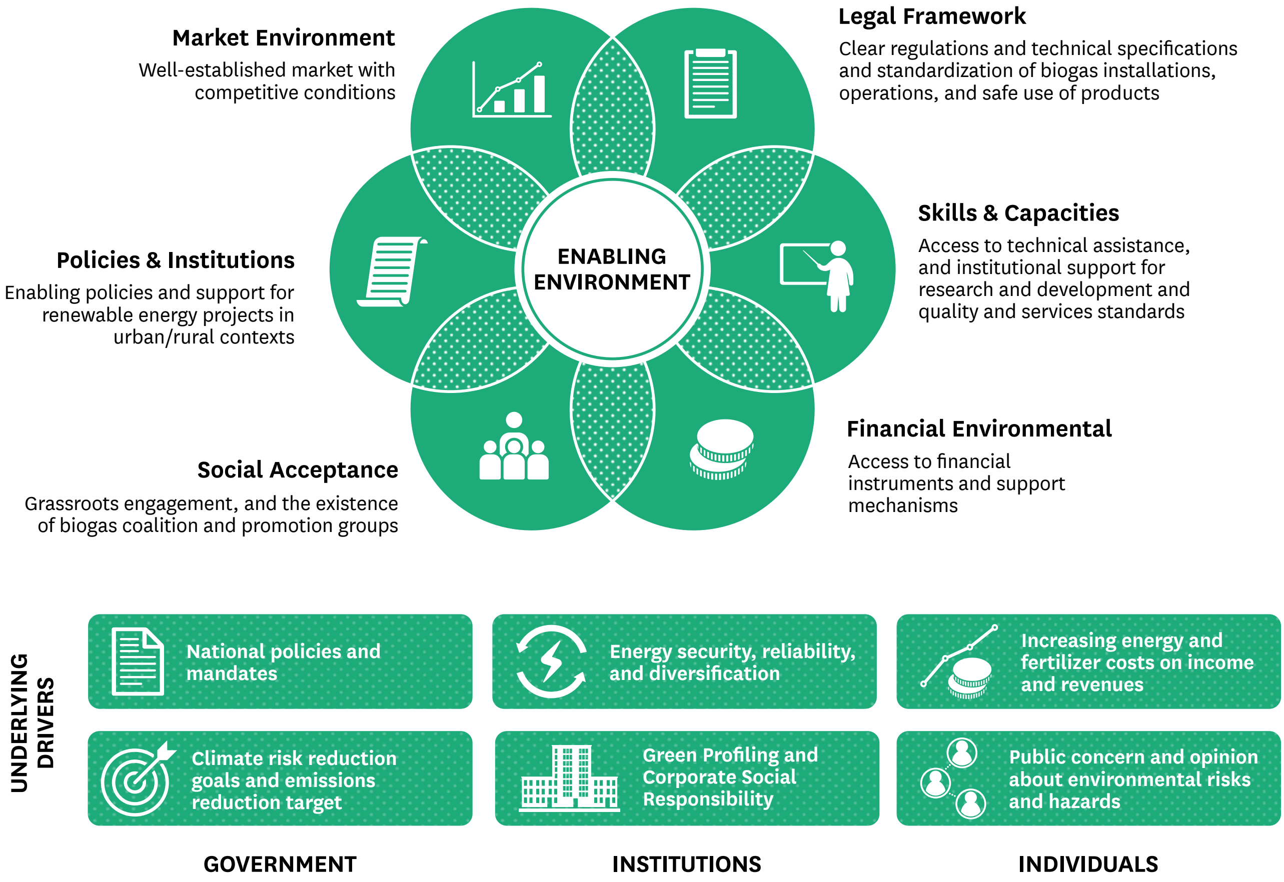


FIGURE 4. Underlying drivers and enabling environment for biogas technologies in LMICs.

Source: Authors.

4

BARRIERS TO LARGE-SCALE IMPLEMENTATION OF BIOGAS TECHNOLOGIES

This section draws out insights and lessons on the barriers and challenges posed to biogas technology implementation for the consideration of policymakers, academics, and practitioners. To get a holistic understanding of the macroenvironment in which these technologies operate and the constraining influences exerted on them by contextual factors, the multicriteria analysis framework presented in Figure 3 was applied to the different case studies and reviews considered for this report. Our focus was on wide-scale rollout (e.g., community-scale plants, biogas systems operated on large farms, and medium- to large-scale production systems for electricity and heat) rather than household biogas digesters. Our approach spanning multiple regions and countries, as well as our consideration of different dimensions, ranging from political to institutional aspects, facilitated a multifaceted understanding of the complex issues facing the biogas sector in LMIC contexts.

4.1. Political and Institutional Barriers

Due to the increasing need for clean and environment-friendly cooking fuel, the biogas policy frameworks employed in LMICs have often evolved from promotional initiatives for small-scale biogas digesters. Large-scale biogas sector development is hindered by key barriers, which fall under four themes: (i) subsidy dependency; (ii) fragmented and weak policy framework and top-down policy approaches; (iii) weak institutions and incentive schemes; and (iv) private sector involvement (Table 5).

Subsidy dependency was found to have been a major barrier to the wide-scale implementation of biogas plants in China, India, Nepal, Uganda, and other African countries (Giwa et al. 2020; Namugenyi et al. 2022; Raha et al. 2014; Thapa et al. 2021; Kemausuor et al. 2018). Indeed, most LMIC countries introduce subsidy schemes to encourage the construction of biogas plants rather than adopt market-based approaches like feed-in tariffs and access to finance. While subsidy schemes are well-appreciated, particularly in the early years, overdependence on subsidies can distort the market by artificially lowering biogas production costs. Creating dependency on government support is counterproductive if the objective is to develop a self-sustaining market. For example, the Chinese government invested heavily in subsidies and grants for the construction of biogas digesters, but that only led to massive inefficiencies, resulting in disincentivizing innovation and efficiency improvement in biogas production processes (Zhou et al. 2021).

Furthermore, the biogas market in many LMICs is largely driven by government and development partner intervention. Often, these institutions are unable to support wide-scale medium- to large-scale quality biogas plants over the long term due to budgetary constraints and competing priorities. Private sector involvement is limited. In Uganda, for example, donation-based biogas activities led to the so-called “free of caste”[1] and “free of service”[2] promotion model, in which biogas technology is donated but with no provision for maintenance and servicing (Namugenyi et al. 2022). As a result, users took no responsibility for and ownership of such plants, which lay unrepaired in case of failure.

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[1] An environment where people are not discriminated against, given special advantages or restricted based on their caste.

[2] Free from specific duties or obligations, especially those associated with servitude or mandatory services.

A large biogas plant in North Carolina. Photography by Shaun Edward Lee

Another challenge is the lack of coordination of policies and institutions, which results in ineffective implementation. A top-down approach to policy development that does not consider the local contexts and stakeholders is also a problem. Technology benefits different sectors, and countries typically set up policy targets and incentives for each sector, such as energy, waste, agriculture, and even industry. Coordination of policies can help in achieving optimum results. For example, in the energy sector, the expansion of biogas technology contributes to achieving the target of increasing the renewable energy mix. Similarly, NAMA[3] commitments mandate GHG emission reduction targets in the waste sector, the attainment of which can be helped by setting up biogas plants for organic waste management. However, despite having similar characteristics, such as the use of grants, collaboration with local entities, and paucity of training and monitoring-evaluation systems, these programs often lack effective coordination. For example, in Indonesia, seven national government biogas initiatives share similar governance structures and features; yet, biogas initiatives are dispersed across various departments under different ministries. These ministries justify their biogas programs based on diverse issues like the energy mix, climate change mitigation, food security, and forest conservation. Lack of collaboration hinders the achievement of broader targets for renewable energy dissemination and emission reduction (Budiman 2021). Similarly, limited coordination between stakeholders located in different sectors was identified as a bottleneck for biogas promotion in China and some African countries (Giwa et al. 2020; Kemausuor et al. 2018). Overall, fragmentation across institutions and policy frameworks has led to inefficiencies, inconsistencies, and duplication of effort at different levels of government. Budiman (2018; 2021) found that lack of cooperation and coordination between institutions in Indonesia resulted in jurisdictional overlapping and poor distribution of biogas projects and initiatives. Fragmented governance and weak institutions had mixed impacts on small- and medium-scale biogas programs, e.g., restricting opportunities to construct high-quality biodigesters and hindering effective monitoring and evaluation. Similar findings of a lack of coordination between different national and subnational governments and public agencies and private sector organizations have been reported from India (Mittal et al. 2018) and Rwanda (Rupf et al. 2015).

Another hindrance to the wide-scale implementation of biogas plants is the inadequacy of incentive schemes to make biogas a competitive technology. Some countries still subsidize LPG and other fossil-fuel energy resources, which in effect reduces the economic viability of biogas plants (Saha et al. 2022; Namugenyi et al. 2022; Kemausuor et al. 2018). In rural settings, biogas plants face stiff competition from options such as traditional solid biomass as they are more affordable (Mittal et al. 2019). For example, in countries like Ghana, the lack of a national biogas policy has disadvantaged biogas technologies, limiting their competitiveness vis-a-vis other renewable energy sources or cheaper alternatives like fuel wood and LPG (Osei-Marfo et al. 2018). In Ghana and other African countries, there is government support for biogas programs and initiatives; however, the lack of a feed-in tariff for biogas-based electricity makes the technology less valuable (Kemausuor et al. 2018).

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[3] Nationally Appropriate Mitigation Actions (NAMA) refers to a set of policies and actions that countries undertake as part of their commitment to reduce GHG emissions.

TABLE 5. Key policy and institutional barriers to biogas technologies.

Theme	Barriers	References
Subsidy dependency	Subsidy-driven biogas market with limited commercial interest	Giwa et al. 2020; Namugenyi et al. 2022; Raha et al. 2014; Thapa et al. 2021; Kemausuor et al. 2018
Weak policy framework	Fragmentation of policy framework and incentive schemes	Budiman 2021
	Top-down policy approach	Mittal et al. 2019; Raha et al. 2014
	No provision for monitoring and evaluation mechanisms	Budiman 2021; Namugenyi et al. 2022
	Large regional differences in the development of large-scale biogas projects	Giwa et al. 2020
	Subsidies for fossil fuel-based energy, leading to limited competitiveness of biogas	Saha et al. 2022; Namugenyi et al. 2022; Kemausuor et al. 2018
	Lack of feed-in tariff for biogas-based electricity	Kemausuor et al. 2018
	Environment law does not allow the use of digestate	Saha et al. 2022
Inadequate institutions	Weak institutional framework and slow implementation	Kemausuor et al. 2018
	Difficulties to sign power purchase agreements	Kemausuor et al. 2018
	Limited coordination between stakeholders in different sectors	Giwa et al. 2020; Budiman 2021; Mittal et al. 2019; Kemausuor et al. 2018
Private sector involvement and financing	Low private sector involvement, including banks	Giwa et al. 2020; Budiman 2021; Namugenyi et al. 2022; Raha et al. 2014; Mittal et al. 2019

4.2. Economic Barriers

The potential for generating revenue from organic waste streams through the production and sale of biogas and soil conditioners or through agricultural use presents significant opportunities for cost recovery and savings. However, the challenge lies in making the substantial investments that are required for infrastructure development, which includes the purchase and installation of digesters and operating, repair, and maintenance costs. Table 6 highlights the key economic and financial barriers to wide-scale implementation of biogas technologies.

TABLE 6. Key economic and financial barriers to wide-scale implementation of biogas technologies.

Economic barriers	References
High upfront capital costs for infrastructure development, including the cost of digesters. Plus, high operating, repair, and maintenance costs, including spare parts and labor.	Nevzorova and Kutcherov 2019; Patinvoh and Taherzadeh 2019; Rupf et al. 2015; Song et al. 2014; Kabyanga et al. 2018
Lack of financing options and credit facilities; low suitability of financing schemes.	Raha et al. 2014; Ahmad et al. 2023; Kemausuor et al. 2018
Lack of an enabling economic environment, such as incentives to encourage investment in biogas solutions.	Budiman 2021; Namugenyi et al. 2022; Raha et al. 2014; Mittal et al. 2019
Low private sector involvement, including by banks	Giwa et al. 2020; Budiman 2021; Namugenyi et al. 2022; Raha et al. 2014; Mittal et al. 2019

High installation and operating costs and limited access to finance are the key economic barriers limiting the spread of biogas technologies in the Global South (Nevzorova and Kutcherov 2019; Patinvoh and Taherzadeh 2019). Of these, high installation costs are the most significant (Rupf et al. 2015; Nevzorova and Kutcherov 2019). There are several reports on this from Bangladesh (Hasan et al. 2022), South Africa (Shonhiwa et al. 2023), Rwanda (Mukeshimana et al. 2021), and other African countries (Amigun and von Blottnitz 2010; Kemausuor et al. 2018). For example, studies by Kabyanga et al. (2018) showed that flexible balloon digesters are increasingly being used as domestic digesters in Uganda, but the installation costs[4] are as high as 60 percent of the total cost. Further, the payback period for the digesters was longer than their economic life and the net present value was negative due to high installation costs (reportedly due to import costs) and low willingness of users to pay for the biogas plants (which in turn is linked to low household income). In fact, the cost users are willing to pay for a new digester was 10 times less than the actual cost of the digester.

An analysis of 38 fixed-dome biogas installations (ranging from small- to large-scale) across 12 African countries (Table 7) showed that community- to large-scale biogas plants are not affordable to end-users, and economies of scale do not apply to small- and institutional-scale biogas plants (Amigun and von Blottnitz 2010). In other studies (Song et al. 2014; Patinvoh and Taherzadeh 2019), the estimated cost of constructing and installing a large-scale biogas plant with integrated pretreatment, comprehensive biogas slurry utilization, and post-treatment biogas refinery storage and transport systems was reported to be about USD 1,000 to USD 1 million, depending on the size of the digester and the scale of operation. These high upfront costs are significant and beyond the means of low-income users (Song et al. 2014; Rupf et al. 2015). Thus, to make biogas plants financially viable for most users, a 50 percent reduction in installation costs was recommended (Kabyanga et al. 2018). This could take the form of financial support, access to finance, or strategies that encourage sustainable local manufacturing and markets (Song et al. 2014). For low-income regions, biogas plants under 8 m^3 are recommended as they are deemed economically viable with a positive net present value, a payback period of less than 3 years, and a high internal rate of return of over 110 percent in most cases (Halder et al. 2016; Ali and Al-Sa'ed 2018). For example, a cost-benefit analysis by Winrock International (Renwick et al. 2007) showed that for an integrated biogas, sanitation, and latrine biogas program, the average financial internal rate of return in Sub-Saharan Africa was about 7.5 percent (8 percent in Uganda, 9.5 percent in Rwanda, and 10.3 percent in Ethiopia). The main barrier to wide adoption was the cost of installation, which had a significant impact on household finances.

A related challenge is high operational costs often leading to reduced profitability (Wu et al. 2021). Operating large-scale waste management facilities requires significant expenses because of the substantial quantities of waste and by-products that must be handled and the extensive mechanized pre- and posttreatment equipment or processes needed. In this respect, Patinvoh and Taherzadeh (2019) cited the nonavailability of commercial loans to invest in biogas infrastructure, mechanical equipment, and technical expertise as major economic barriers to wide-scale biogas implementation. This includes the operational costs incurred to keep a continuous flow of organic material, by-products that need to be continuously moved, and other operational requirements to maintain an optimum temperature in the digester. In other studies (Zhou et al. 2021; Ali et al. 2021; Saha et al. 2022; Osei-Marfo et al. 2018), high operational costs are associated with frequent maintenance and repairs of digesters and lack of spare parts, which reduces plant viability. Figure 5 illustrates the average costs of biogas technologies per unit of energy produced in 2018 (IEA 2020).

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[4] Installation costs include expenses incurred for the construction of the digester and associated infrastructure, as well as money spent on hiring and training of technical staff and procuring mechanical and electrical equipment.

TABLE 7. Fixed investment costs of biogas installations in some African countries.

S/N	Plant location	Capacity (m^3)	Year built	Original cost[a]	Cost normalized to ENR index 2004 (USD)[b]
1	Namibia	4	1999	USD 750	860
2	Ethiopia	4	2000	USD 554	618
3	South Africa	5	2002	ZAR 5,000	504
4	South Africa	5	2003	ZAR 5,000	685
5	Nigeria	6	1999	USD 763	874
6	Rwanda	6	2004	USD 1,016	1,016
7	Ghana	6	2004	USD 1,358	1,358
8	Uganda	6	2004	USD 1,005	1,005
9	Burkina Faso	6	2004	USD 1,029	1,029
10	Kenya	8	2004	USD 1,535	1,535
11	Nigeria	10	2005	NGN 492,100	3,565
12	South Africa	10	2001	ZAR 20,000	2,541
13	South Africa	11	2004	ZAR 23,000	3,487
14	Rwanda	16	2004	USD 2,000	2,000
15	Rwanda	16	2004	USD 25,000	2,500
16	Zimbabwe	16	2004	ZWL 2,212,804	3,173
17	Kenya	16	2004	USD 2,198	2,918
18	Kenya	16	2004	USD 2,793	2,793
19	Ghana	20	2000	USD 7,974	8,901
20	Ghana	20	1996	USD 750	6,334
21	Lesotho	31	2004	USD 7,132	7,132
22	South Africa	40	2002	ZAR 97,000	9,784
23	Burundi	50	2002	USD 18,000	19,118
24	Kenya	54	2004	USD 12,176	12,176
25	Rwanda	74	2002	RWF 7,150,000	15,943
26	Rwanda	74	2003	RWF 7,800,200	15,050
27	Rwanda	84	2004	RWF 9,188,010	15,990
28	Ghana	100	1999	USD 39,120	44,835
29	Kenya	124	2004	USD 26,090	38,090
30	Rwanda	650	2002	RWF 50,870,000	127,318
31	Rwanda	830	2003	RWF 58,086,270	112,073
32	Rwanda	1,000	2004	USD 220,000	220,000

Continued >

S/N	Plant location	Capacity (m^3)	Year built	Original cost[a]	Cost normalized to ENR index 2004 (USD)[b]
33	Rwanda	1,430	2005	RWF 96,466,000	173,835
34	South Africa	4,500	2004	USD 1,671,429	1,671,429
35	Nigeria	5,000	2004	USD 420,000	420,000

Notes:

[a] USD = US dollar; ZAR = South African rand; NGN = Nigerian naira; ZWL = Zimbabwean dollar; RWF = Rwandan franc.

[b] Data were first converted from local currency to USD at the rate applicable in the year of construction, then corrected using the ENR index of 6944 (2004) to account for cost escalation with time and for data comparability.

Source: Amigun and von Blottnitz 2010.

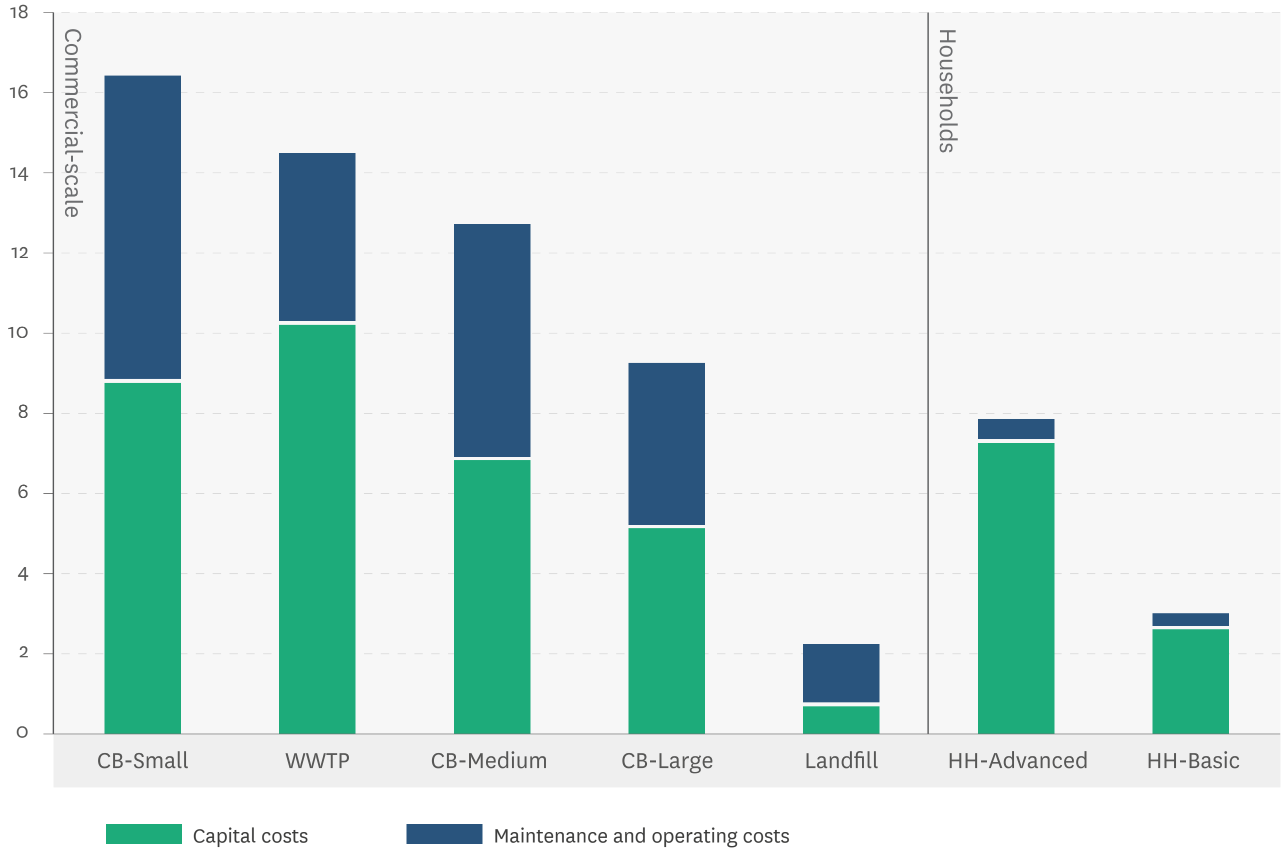

FIGURE 5. Average costs of biogas production technologies per unit of energy produced in 2018 (excluding feedstock).

Source: IEA 2020.

Notes:
Commercial biodigesters (CB) are categorized as small (100 m^3/h), medium (250 m^3/h), and large (750 m^3/h) in terms of the output flow rate. Wastewater treatment plants (WWTPs) are designed to process 1,000 m^3/h of municipal sludge. Landfill gas recovery systems are designed to process 2,000 m^3/h of closed landfill gas. 'HH (household) Basic' includes biodigesters constructed in place using traditional construction materials such as sand, gravel, and cement; 'HH Advanced' includes premanufactured biodigesters made of more expensive composite material. Maintenance and operating costs include ordinary and extraordinary maintenance, labor costs, and energy required to operate the system. Capital costs have been levelized for the production lifetime of each technology: 25 years for landfill gas recovery and advanced household biodigesters; 20 years for centralized biodigesters (small, medium, and large) and wastewater digesters; and 15 years for basic household biodigesters. 1 MBtu = 0.29 MWh.

As mentioned earlier, most biogas markets in the global south are driven by government subsidies rather than market-based incentive mechanisms. Hence, another barrier to biogas technology is the lack of financial assistance and government subsidies, along with financing options and credit facilities provided by local banks, coupled with low interest rates. Financing schemes are often not available, or not widely available; where they do exist, they are not targeted to users and the poorer strata of the population, who have more difficulties accessing finance (Raha et al. 2014; Ahmad et al. 2023; Thapa et al. 2021; Kemausuor et al. 2018). Linked to the challenge of accessing finance is the low involvement of the private sector, which has been identified as a bottleneck in China, India, Indonesia, and Uganda (Giwa et al. 2020; Budiman 2021; Namugenyi et al. 2022; Raha et al. 2014; Mittal et al. 2019). Private companies and investors are reluctant to invest due to low economic viability and other market risks. These risks often take the form of lower prices and high availability of alternatives such as fuel wood, LPG, and kerosene; fluctuating energy prices; seasonality and vulnerability of biogas systems to external factors such as climate conditions; uncertainty of biogas quantities and qualities; and shifting consumer preferences (Saha et al. 2022; Nevzorova and Kutcherov 2019; Kemausuor et al. 2018). Addressing these challenges and barriers requires institutional arrangements and coordination and engagement of various actors, including government organizations, international development agencies, finance institutions, and private companies (Ortiz et al. 2017).

4.3. Sociological Barriers

Sociological factors have been widely reported as obstacles to the implementation of biogas technologies in LMICs. Factors such as adverse user perceptions and socioeconomic conditions have been found to inhibit the adoption of biogas technologies and, by extension, their widespread implementation. Table 8 highlights the significant socioeconomic and sociocultural barriers limiting the diffusion of biogas technologies in the global south.

TABLE 8. Key socioeconomic and sociocultural barriers to the implementation of biogas technologies.

Sociological barriers	References
Disparities of gender, age, and size of household; low levels of education and social status; limited ownership of assets, including livestock; geographical disparities and inequalities.	Kelebe et al. 2017; Kabir et al. 2013; Mittal et al. 2018; Mwirigi et al. 2014; Katuwal 2022; Talevi et al. 2022; Walekhwa et al. 2009; Das et al. 2017; Wang et al. 2020
Negative perceptions of biogas due to cultural, social, or religious beliefs, e.g., cultural barriers associated with traditional cooking customs	Shane et al. 2015; Williams et al. 2022; Osei-Marfo et al. 2018; Bekchanov et al. 2019; Gebreegziabher et al. 2014; Dumont et al. 2021
Poor perception of biogas due to past failures; lack of confidence and trust in the technology	Kelebe et al. 2017; Mittal et al. 2018; Mwirigi et al. 2014
Resistance to change and innovation	Hasan et al. 2022; Williams et al. 2022
Lack of a sense of ownership and the willingness to pay	Budiman 2021; Wassie and Adaramola 2020; Talevi et al. 2022; Kabyanga et al. 2018
Lack of direct engagement with actors in the sector	Büscher 2023
Low property and land rights	Kelebe et al. 2017; Katuwal 2022

Several studies [Kabir et al. (2013), Mwirigi et al. (2014), Kelebe et al. (2017); Williams et al. (2022)] have found that demographic factors such as age, gender, ethnicity, level of education, family size, social class, and assets owned influence the acceptance and adoption of biogas technologies. While variables such as low income and high unemployment have financial implications, others, such as education and social status, exert an influence through norms and beliefs. In Ethiopia and Bangladesh, households led by women were more likely to adopt biogas technologies than those led by men (Kabir et al. 2013; Kelebe et al. 2017). In Kenya and Nepal, male-led households tended to adopt biogas technology sooner because they have greater access to, ownership of and decision-making power over productive resources (Mwirigi et al. 2014; Mittal et al. 2018; Katuwal 2022). It was also observed in Kenya and Nepal that older adults are more likely than younger people to adopt biogas technology. That is because they are more likely to have accumulated wealth and can afford the initial cost of construction and installation. Furthermore, older people tend to own more livestock, have a higher economic status, and greater experience, which makes them better equipped to manage a biogas plant. In some cases, however, age was inversely related to biogas adoption. For instance, in Uganda, older heads of households were more risk-averse and less willing to adopt innovations (Walekhwa et al. 2009). Similarly, in India, risk aversion and impatience with the long time it takes to derive benefits from biodigesters were associated with a lower willingness to pay for biogas technology (Talevi et al. 2022). Households with more livestock or people were more likely to install biogas plants because they had the feedstock and the people to carry out manual labor of loading the digesters (Walekhwa et al. 2009; Kelebe et al. 2017).

Low levels of education have been linked to difficulties in the adoption of technologies. A higher level of education increases the probability of biogas adoption; limited literacy may permit only a limited understanding of the information regarding biogas technology. However, in some countries, such as Uganda, heads of households with formal education were less likely to adopt biogas. This could be because people with formal education generally have more income and live in urban areas where they can access other sources of energy, such as electricity and

Solids from biogas effluents is dewatered and pressed as cakes for fuel. Photography by India Water Portal

LPG, which they may find more convenient (Walekhwa et al. 2009). Furthermore, low adoption of biogas technology among those with formal education could also be because of poor perception and association of biogas technologies with poor communities. Generally, however, it is households belonging to disadvantaged socioeconomic groups that are less likely to adopt biogas technology. For example, in Nepal, the Brahmins, who are the most socially privileged caste group, are more likely to adopt biogas than people of other castes and social identities (Katuwal 2022). Similarly, in India, people in the lower social strata were reported to be less likely to adopt biogas (Das et al. 2017). Such socioeconomic conditions can make biogas technologies financially inaccessible.

Lack of awareness and understanding of the benefits of biogas, coupled with adverse social norms and perceptions, can impede acceptance of biogas technologies. Some beliefs and perceptions, which could be social, cultural or faith-based, particularly around the feedstock used for biogas production, influence the adoption of biogas technology. In one part of Zambia, for instance, a traditional belief that women are not allowed to handle cow dung led to the failure of a biogas project because the empowered beneficiaries could not feed their digesters (Shane et al. 2015). In Assam state of India, implementation of a domestic toilet-linked biogas project faced challenges due to cultural taboos around working with and cooking with gas derived from human feces and the perception that working with filth or human excreta is linked to low social status (Williams et al. 2022). Some specific perceptions that contributed to the rejection of domestic toilet-linked biogas technology in India entailed the risk of social exclusion, judgment, and the threat of social sanctions from the wider community; the risk of contravening religious practices and sentiments; and the belief that it is not customary (or even criminal) to mix human excreta with cow dung (Williams et al. 2022). The use of animal and human excreta as feedstock in biodigesters is subject to widespread stigmatization as it is perceived as contaminated (Osei-Marfo et al. 2018) and religiously inappropriate. Low-income communities in South Africa were more likely than high-income communities to perceive biogas as contaminated, although both groups perceived it as risky (Dumont et al. 2021). Because of the nature of organic waste materials, biogas is often perceived as less natural and harmful and elicits physical and moral disgust and fear compared to other renewable energy technologies. Social stigma around the use of human excreta as feedstock was a reason for the rejection of biogas adoption in Sri Lanka (Bekchanov et al. 2019). Stigmatization is also seen in some religions in Africa due to strict cleanliness rules, which limits the adoption of biogas due to the use of human and animal excrement (Gebreegziabher et al. 2014).

The failure of biogas projects in many countries, including Ethiopia (Kelebe 2018), Kenya (Mwirigi et al. 2009), and India (Mittal et al. 2018), has generated a poor perception of and reduced trust in biogas technologies. Some of these failures were the result of financial mismanagement or inadequate funding or operational issues such as technical difficulties, inadequate maintenance, or insufficient training. Furthermore, lack of community support and resistance to change gave rise to skepticism about the sustainability of biogas initiatives. Such perceptions can erode trust in the reliability and effectiveness of biogas technologies. Resistance to the adoption of specific biogas technologies is often rooted in the sense of identity and the personal and social norms held by people (Hasan et al. 2022; Williams et al. 2022). This undermines any efforts made toward diffusion of the technology and results in users' unwillingness to pay for it. Budiman (2021) provides examples of households that were required to pay only a small initial fee to receive a grant for the installation of a biogas plant. However, this made the households perceive that the biogas plant was not theirs, indicating the lack of a sense ownership. They took no responsibility and invested little time and effort in maintaining the plant. Examples are cited in other publications of households deliberately avoiding the operation and maintenance of their digesters to save money. Some households assume that if their plant fails or is not in operation, they will not have to repay their loan (Wassie and Adaramola 2020). While some households, e.g., in India and Nepal, were willing to pay a premium or most of the cost of a new biogas digester (Talevi et al. 2022; Thapa et al. 2021), those in Uganda were only willing to pay about 10 percent of the cost (Kabyanga et al. 2018; Wassie and Adaramola 2020).

The geographical characteristics of a community could also be a barrier to adopting biogas technology. Katuwal (2022) showed that households in Nepal's mountainous regions were less likely to adopt biogas due to the altitude, which makes installation difficult, or the low temperatures, which make it unsuitable for biogas production. Wang et al. (2020) reported that biogas was better promoted in southern rural China, which has higher temperatures, than in the colder, northern areas of the country. Katuwal (2022) showed that medium-sized landholders in Nepal were more likely to install and use biogas than marginal landholders. Kelebe et al. (2017) showed that in rural Ethiopia, the suitability of a site rather than the land size determined the uptake of biogas technology.

To overcome these challenges, it is crucial to address the root causes of project failure, implement effective community engagement strategies, provide ongoing support and training, and communicate transparently the lessons learned and the improvements needed. It is also important for biogas project funders and implementers to engage directly with the targeted beneficiaries. In Mozambique, a biogas pilot project, PO15, was unsuccessful largely because there was limited direct engagement with key local and national agents and end-users (Büscher 2023). The Water and Sanitation Infrastructure Management Agency of Mozambique, the public agency responsible for water supply and sanitation, was largely excluded from the process as the agency was unfamiliar with the technology and had divergent expectations of the business models of the pilot project. Furthermore, end-users in the targeted communities were not directly consulted during project planning and implementation but were only made aware of the project. The engagement was indirect, consulting only the municipality as a representative of the people.

4.4. Technical Barriers

Several technical issues have been reported to significantly delay and, in some cases, reverse progress in scaling up biogas technologies in the global south (Osei-Marfo et al. 2018; Kalina et al. 2022). Table 9 summarizes some of the commonly reported technical barriers.

Operational and maintenance challenges have been cited as the main cause of nonfunctioning biogas facilities. Saha et al. (2022) surveyed 16 commercial poultry- and dairy-fed digesters in Bangladesh and found that they had stopped working after one or two years of operation due to limestone sediments and inlet blockage. Repairs and maintenance required downtime and entailed substantial costs. In Ghana, one digester designed to be fed with cow dung could not be operated when fecal sludge was used as feedstock due to the inability to access or offload the digester (Osei-Marfo et al. 2018). Inlet blockage usually occurs due to poor design or improper particle size of the feedstock. High amounts of fibrous material, e.g., straw or total solids as in the case of cow dung, can clog the inlet (Vögeli et al. 2014). Too large a particle size can make it difficult for bacteria to decompose the feedstock (Ngan et al. 2019). Poor design of the inlet can be a contributing factor too, particularly if the slope is insufficient or if the diameter of the pipe is not big enough.

TABLE 9. Key barriers relating to technical factors.

Technical barriers	References
Lack of appropriate adaptability of biogas technologies; poor construction and installation issues	Giwa et al. 2020; Saha et al. 2022; Raha et al. 2014; Vögeli et al. 2014
Lack of feedstock supply and poor quality of waste streams; resource constraints, including water and land	Osei-Marfo et al. 2018
Critical infrastructure barriers, e.g., access to electricity grid, gas grid, connections, and networks	Kemausuor et al. 2018; Song et al. 2014; Zhou et al. 2021
Operation and maintenance challenges, including technical skill/know-how; technical complexities, and lack of experience in implementing biogas projects	Budiman 2021; Ahmad et al. 2023; Bekchanov et al. 2019; Tavera-Ruiz et al. 2023; Ali et al. 2021
Poor accounting and understanding of the wider benefits, e.g., waste treatment services and nutrients	Tavera-Ruiz et al. 2023
No or low gas yield due to poor operation of the digester and complexities of operation and maintenance.	Osei-Marfo et al. 2018; Ngan et al. 2019; Saha et al. 2022

Abandonment of biogas projects due to technical issues is widespread in LMICs, particularly in Asia and Africa. Mass failures or low technology transfer rates have been reported in Ghana (Osei-Marfo et al. 2018), northern Tanzania (Hewitt et al. 2022), Senegal (Diouf and Miezan 2019), Colombia (Tavera-Ruiz et al. 2023), China (Zhou et al. 2021), Sri Lanka (Bekchanov et al. 2019), and Pakistan (Ali et al. 2021). The often-cited reasons for abandonment of digesters include poor or no gas yield, and the high cost of maintenance and repairs. For example, Zhou et al. (2021) reported a biogas yield of 106-222 m^3 CH_4/t_{ODM} for three large-scale digesters in Beijing compared to 234-354 m^3 $CH_4/t_{ODM.}$ obtained in Germany. This suboptimal performance of China's biogas plants was attributed to lower substrate input and mono digestion, lower working temperature, and sedimentation in the digesters due to improper mixing. Tavera-Ruiz et al. (2023) reviewed 996 out of 5,700 digesters installed in Colombia and identified technical complexities and lack of experience in implementing biogas projects at scale as the major causes of slow adoption and limited large-scale implementation. Performance tended to be suboptimal due to the prevalence of low-cost tubular digesters and their operation in psychrophilic conditions. The underdevelopment of the large-scale digester sector has also been attributed to inadequate financing of biogas projects, stemming from a poor perception of the risks and low accounting of the wider benefits of biogas. Sri Lanka has no experience with a commercial-scale biogas plant, although a large-scale waste-to-energy plant is now said to be under construction to process the organic fractions of municipal solid waste (OFMSW) that would otherwise end up in the Karadinyana landfill (Bekchanov et al. 2019). As for medium- to large-scale biogas plants, underdevelopment is mainly due to poor installation, use of low-quality construction materials, inadequate care of the plant, and less technical factors. Some 28 percent of the domestic biogas plants fail within 10 years of operation, resulting in widespread user dissatisfaction and indifference to the technology. Other causes of failure include the scarcity of technical skills and know-how by operators, leading to poor feedstock choices, and improper management and separation of organic wastes—such that plastic was allowed into the digesters in some cases.

Several studies on the spread of biogas technology report that uncertainties in the supply of feedstock could lead to failure too (Bekchanov et al. 2019). This is because of limited consideration of the quality, variability, and uncertainty of feedstock supply, including spatial and temporal distribution of waste resources. In the LMIC context, it is often assumed that waste resources are abundant, always available, and easy to source at no cost due to volumes of visible waste and the status of waste management practices, but case studies prove otherwise (Osei-Marfo et al. 2018; Bekchanov et al. 2019). For example, market waste and municipal solid waste may not always be suitable for use as feedstock; in most cases, the organic fraction is not more than 50 percent. The use of such material without segregation or pretreatment can lead to poor gas yields. Moreover, the separation of waste comes at a cost, which is often not considered, and long-distance transportation can erode the expected economic and environmental benefits of installing a digester.

Beyond these reasons, the lack of waste treatment and storage facilities and other resource limitations such as land and water can lead to technology abandonment too. Further, the absence of a biogas transmission and distribution network, including underground pipelines and connections to the national grid, constrains growth as well. Osei-Marfo et al. (2018) surveyed 54 digesters in Central and Greater Accra and observed that most of the institutional digesters were not connected to cook stoves or power-generating units. Tavera-Ruiz et al. (2023) also highlighted the weak integration of biogas technologies into agricultural systems. Consequently, opportunities to recover energy from waste streams are widely missed. For example, only a small number of the surveyed large-scale plants utilized the biogas produced for their energy needs or injected it into the grid; most of them (about 70 percentt) expelled the gas by converting the CH_4 into CO_2. In China, Song et al. (2014) and Zhou et al. (2021) reported that many of the medium- to large-scale biogas plants were situated in rural farms but depended on grid electricity for their own energy needs because the cost of installing and integrating a combined heat and power plant was high. Tavera-Ruiz et al. (2023) reported that using biogas in internal combustion engines was problematic due to carbon and sulfur deposition on the spark plugs. Also, power-generating equipment utilizing biogas products tended to consistently fail, leading to increased maintenance expenses. Furthermore, maintenance challenges were compounded by uncertainties about post-warranty servicing and human factors such as the scarcity of trained labor, limited know-how, and poor awareness of biogas technology. The nonavailability of measuring and monitoring equipment (e.g., pressure gauges and flow meters) also hindered the capacity to measure the pressure and flow of gas. These various technical factors combine to hinder the growth of the biogas sector in LMICs.

4.5. Legal Barriers

To establish large-scale biogas facilities for communal or commercial purposes in a particular country, there needs to be a comprehensive and supportive policy and legislative framework in place. However, that is not the case in many countries. Where regulatory frameworks for biogas sector development do exist, they often are not targeted or embedded in other frameworks. This limits private investment in the sector and creates bureaucratic hurdles for entrepreneurs (Schmidt and Dabur 2014). India and Senegal are examples of countries where such nontargeted regulatory frameworks for the private sector and consumers exist (Schmidt and Dabur 2014; Mittal et al. 2018; Diouf and Miezan 2019). In India and China, there are large-scale plants producing biogas that can be compressed, upgraded or utilized as a transportation fuel, but the necessary guidelines or regulations to enable their integration into the existing gas grid or use in internal combustion engines are missing. High levels of bureaucratic functioning are cited in the literature, and in India, many bio-methanation plants have been reported to fail despite technological maturity due to extensive legal and administrative processes. For example, clearance for a 100 kW project in Haryana state is said to take 15 months, and approvals are needed from 16 state departments (Schmidt and Dabur 2014). There are no niche markets for biogas, and environmental plans are not integrated into the country's development plans, leading to poor legitimization of biogas projects. Due to complex institutional arrangements and the unclear legislative framework, some project developers could not obtain regulatory approvals and permissions from the mandated departments (Schmidt and Dabur 2014; Mittal et al. 2018). Similar bureaucratic hurdles have been highlighted in countries like China (Nevzorova and Kutcherov 2019), Bangladesh (Hasan et al. 2022), Brazil (Perez Ribeiro and Possetti 2022), and Indonesia (Taylor et al. 2019). In China, a clean development mechanism project took approximately 18 months to complete, as opposed to 3 months in Austria (Nevzorova and Kutcherov 2019). The average registration period for similar projects was reported to be about a year or more.

There is also a major issue with the absence of standards with respect to biogas installation, operation, and maintenance. Service providers are not obligated to meet certain standards or requirements, resulting in poorly installed biogas facilities and over- or undersizing of digesters (De Oliveira and Negro 2019). Other examples encountered in literature also point to a lack of clear guidelines on digester design and operations, e.g., how biogas can be used as a transportation fuel (Issahaku et al. 2024; Mittal et al. 2018); standards and certifications that can ensure that biogas plant operations and products comply with health, safety, and environmental regulations (Wang et al. 2020); land-use guidelines for sustainable development of large-scale biogas projects including aspects of feedstock supply, logistics, and environmental discharge (Sovacool et al. 2015; Osei-Marfo et al. 2018); and lack of a regulatory framework for funding and financing (Nevzorova and Kutcherov 2019; Kemausuor et al. 2018; Patinvoh and Taherzadeh, 2019). In South Africa, Kemausuor et al. (2018) and Nevzorova and Kutcherov (2019) reported that the feed-in-tariff program was an expensive and complex process. Biogas developers were required to bid with high legal costs, and bid bonds were high—about USD 2 million per bid. An example is cited of a commercial biogas plant of 4.6 MW, which incurred USD 0.8 million in legal costs over seven years. Due to legal constraints, surplus electricity could not be fed into the grid by grid-connected biogas plants. Thus, to address this issue, Abanades et al. (2022) suggested the need for a streamlined process for obtaining permits and approvals for biogas facilities. Schmidt and Dabur (2014) and Nevzorova and Kutcherov (2019) emphasized the importance of decentralizing the highly hierarchical nature of programs. They also emphasized the need for a unified regulatory body, formal industry associations, and networks of actors to address the problem. Table 10 highlights the significant legal barriers limiting the wide-scale implementation of medium- to large-scale biogas plants.

TABLE 10. Key barriers relating to legal or regulatory factors.

Legal barriers	References
Lack of targeted regulatory frameworks for biogas sector development and misalignment with government priorities	Schmidt and Dabur 2014; Mittal et al. 2018; Diouf and Miezan 2019
Lack of clear guidelines on digester design and operations, e.g., how biogas products are to be used	Issahaku et al. 2024; Wang et al. 2020
Lack of or limited standards and guidelines for health, safety, and environmental compliance	Wang et al. 2020
Absent or unclear land-use/tenure guidelines for sustainable development of medium- to large-scale biogas projects	Sovacool et al. 2015
Lack of a regulatory framework for adequate funding and financing of medium- to large-scale biogas projects	Nevzorova and Kutcherov 2019; Kemausuor et al. 2018; Patinvoh and Taherzadeh 2019

4.6. Environmental Barriers

Many reports in literature agree that biogas technology provides a number of environmental benefits, including waste and pollution prevention, and opportunities for recycling of organic materials and nutrients (Gebreegziabher et al. 2014; Surendra et al. 2014; Lisowyj and Wright 2018), but few argue that more harm than good is done when the technology is not sufficiently adapted or implemented (Lwiza et al. 2017; Osei-Marfo et al. 2018; Hewitt et al. 2022). Some of the environment-related factors hindering the large-scale development of biogas technologies in LMICs are highlighted in Table 11.

Firstly, biogas production is contingent upon optimum temperature. Various microbial communities thrive in different temperature ranges. Despite this fact, many digesters in LMICs operate at ambient temperatures with limited or no controlled heating conditions. Tavera-Ruiz et al. (2022) reported the use of low-cost tubular digesters at psychrophilic conditions (typically, temperature below 20°C) under which digestion is much slower. In tropical climates, digesters are often not heated and are operated in mesophilic conditions, with a temperature range of 30°C to 40°C (Vögeli et al. 2014). Such uncontrolled heating conditions can make biogas plants vulnerable to climate variability and changing weather patterns. Furthermore, the availability, type, and quality of feedstock can vary across regions. Areas with limited agricultural activity or poor waste management systems may face challenges in sourcing sufficient feedstock for biogas digesters (Osei-Marfo et al. 2018; Hewitt et al. 2022). As areas with warmer temperatures tend to have increased microbial activity, poorly managed waste streams can lose some of their energy or nutrient value before use (Vögeli et al. 2014). Particularly, areas with limited water resources may find it challenging to operate biogas plants. Examples of these challenges are cited in Mittal et al. (2018) and Marie et al. (2021). Also, space can be an issue for biogas plants, especially large-scale plants, and in densely populated areas. All these climate and geographical factors make it difficult to scale biogas technology as they affect the yield of products and increase operational costs.

Another barrier relates to the implementation of local and national environmental strategies and policies that diminish or undermine the effectiveness of biogas technology in achieving carbon mitigation and meeting renewable energy targets. In Indonesia, the government's focus on large-scale electricity generation by geothermal plants became a barrier to biogas diffusion rather than an enabler (Budiman 2021). In Bangladesh, a policy environment that has no measures to regulate the dumping of waste in the environment discourages waste collection and recycling (Hasan et al. 2022). Likewise, the provision of subsidies for fossil fuels like LPG or nutrient sources like chemical fertilizers (Budiman 2021; Situmeang et al. 2022) can limit biogas technology diffusion.

In Asia and Africa, large-scale dissemination of biogas plants has largely been driven by user satisfaction shaped by a feedback system (Clemens et al. 2018; Dumont et al. 2021) that allows a user to try out a product based on hearsay and continue to use it based on service, quality, and sector-wide promotion and development. Where user satisfaction diminishes due to low environmental performance, wide-scale implementation or large-scale development of biogas technology can be limited. Some of the adverse environmental impacts that constrain biogas technology adoption include the release of GHGs into the atmosphere, e.g., due to unintended CH_4 leakage (Paolini et al. 2018; Bakkaloglu et al. 2022); contamination of water sources and spread of pathogenic diseases due to improper treatment or use of digestate products (Alfa et al. 2014); and social conflict due to improper handling and storage of feedstock and by-products (Nevzorova and Kutcherov 2019), leading to unpleasant odors and air quality deterioration. This could also be due to poorly planned biogas projects or inadequate community engagement (Bourdin et al. 2018) causing adverse environmental and health risks and community resistance.

Bio-slurry management is a major issue in LMICs, particularly if resources originate from fecal sources (Bonten et al. 2014; Schoeber et al. 2021; Saha et al. 2022). This can arise from the social stigma often associated with biogas plant by-products (Bekchanov et al. 2019), strict or restrictive regulations on digestate application (Lamolinara et al. 2022), and environmental and health risk concerns (Weckerle et al. 2023). In some countries, digestate is not allowed to be directly applied as fertilizer on agricultural fields, and use options are limited despite a policy environment that promotes biogas technology. Some of these concerns are not unfounded: Saha et al. (2022) reported that only a few commercial farms surveyed in Bangladesh used bio-slurry as fertilizer or for other agricultural purposes; some farmers stored the bio-slurry in pits and emptied the effluents into water bodies or nearby fields. Schoeber et al. (2021) reported improper bio-slurry management in Ethiopia; indications are that bio-slurry has not been applied as fertilizer as widely thought. Similar observations have been reported by Raha et al. (2014) and Hasan et al. (2020). In various contexts, poor bio-slurry management has been attributed to a lack of waste treatment and waste storage facilities, and a lack of awareness. Users are not well-informed about what should be done with digestate, and the nature of the digestate materials makes it hard to apply on agricultural fields.

TABLE 11. Environmental barriers to the wide-scale implementation of medium- to large-scale biogas plants.

Environmental barriers	References
Geographical constraints on the availability of natural or environmental resources such as water, land, and feedstock.	Mittal et al. 2018; Marie et al. 2021
Suboptimal environmental conditions and digester susceptibility to climate variability and change	Tavera-Ruiz et al. 2023; Osei-Marfo et al. 2018; Hewitt et al. 2022
Lack of environmental awareness and education of users	Raha et al. 2014; Hasan et al. 2020
Unsupportive environmental policies and regulations	Budiman 2021; Situmeang et al. 2022
Risk of pathogen spread and disease	Alfa et al. 2014; Nevzorova and Kutcherov 2019
Environmental pollution such as nutrient run-off, soil acidification, and heavy metal contamination	Schoeber et al. 2021; Raha et al. 2014; Hasan et al. 2020

A woman farmer spreading nutrient-rich slurry in her field. Slurry is a by product obtained from a household biogas plant at Akole, Maharashtra, India. Photography by BAIF, India

5

RECOMMENDATIONS FOR LARGE-SCALE BIOGAS SECTOR DEVELOPMENT

Wide-scale diffusion of medium- to large-scale biogas plants needs an enabling environment encompassing a range of supporting policies, institutions, market schemes, and finance facilities. In this section, some recommendations are outlined based on learnings from various reviews and reports on biogas sector development in different countries. Evidence from Europe, China, and India has shown that effective policies and incentive mechanisms can foster the adoption and scaling of biogas technologies (Gustafsson and Anderberg 2022; Abanades et al. 2022).

5.1. A Unified Regulatory Body for Biogas Sector Governance and Coordination

Given that biogas application spans various sectors and industries, including energy, waste management, and agriculture, coordination among relevant ministries and key institutions is paramount. A unified regulatory body for biogas sector management is strongly recommended to facilitate such coordination and to oversee, regulate, and promote the development of the biogas industry (Abanades et al. 2022). This can be achieved by effective collaboration and communication between various stakeholders, including governmental and nongovernmental organizations. Similarly, partnerships that promote knowledge sharing, best practices, and expertise exchange must be fostered toward the same goal. The regulatory body should establish guidelines, standards, and regulations to uphold the quality and dependability of biogas systems. This involves crafting and implementing policies for the safe production, distribution, and use of biogas (Xue et al. 2020; Kanda et al. 2022) and mechanisms for continuous monitoring of compliance with environmental, safety, and health regulations (Huttunen et al. 2014; Wang et al. 2020). This effort involves facilitating holistic planning and innovation with industry stakeholders and enabling continuous improvements through knowledge sharing and partnerships with research institutions. In this mix, clear roles and responsibilities should be assigned at the national, regional, and local governance levels to ensure the effective implementation of regulations and incentive schemes (Kabera et al. 2016; Abanades et al. 2022). Creating a transparent market structure that promotes fair competition and equal opportunities for all stakeholders is crucial. Collaboration with appropriate financial institutions should be facilitated to offer incentives, subsidies, or low-interest loans that would promote investments in biogas initiatives (Suwanasri et al. 2015; Sawale et al. 2020). The decision-making and permitting processes for biogas projects should be streamlined to reduce bureaucratic hurdles (Mukeshimana et al. 2021). More importantly, a long-term strategy is crucial for the industry with respect to infrastructural development, capacity-building, and technology advancement to mitigate risks and encourage direct investment in biogas projects.

5.2. Policies and Support Schemes to Actualize the Full Benefits of Biogas Systems

There are numerous advantages to using biogas systems. They are not limited to producing renewable energy and mitigating GHG emissions. They can be used to produce biofertilizers and preserve water quality, which will enable countries to meet their national climate targets and ambitions. The strength of biogas technologies is their multifunctionality. However, in many use cases reported in the global south (Raha et al. 2014; Osei-Marfo et al. 2018; Schoeber et al. 2021; Tavera-Ruiz et al. 2023), biogas products are not fully utilized. So, policies and support schemes that foster biogas use in key sectors such as energy, transport, agriculture, environment, and waste management are needed. For instance, Sweden has widely promoted the simultaneous use of biogas for energy and transportation purposes, making it a global leader in biogas-fueled transport (Zhu et al. 2019). This was achieved by continually evolving policy instruments such as reducing fringe-benefit tax for alternative vehicles, creating a carbon-differentiated vehicle tax, introducing a tax exemption for biogas use for heating and transportation, and then expanding rural development programs for farm-scale biogas production, among others.

Similarly, Denmark's green growth strategy promotes the use of biogas plants for simultaneous renewable energy generation and organic waste management. It has reduced synthetic fertilizer use by 50 percentt compared to 1985 levels. This was achieved by enacting and consistently evolving legislative drivers and policies that prohibit the landfilling of organic waste material, restrict the use of mineral fertilizer, and encourage the use of organic waste for biofertilizer production (Zhu et al. 2019). China promoted the construction of medium- and large-scale biogas plants by coupling them with medium- and large-scale livestock and poultry farms (Jiang et al. 2011). The initiative increased renewable energy generation, created new jobs, and reduced emissions associated with landfilling of organic wastes. In Germany, various market- and finance-based instruments such as fixed-payment and tradeable certificates were used to mitigate risk and encourage private investment and long-term partnerships in the biogas sector (Thrän et al. 2020). Such policies and extended-use services can be introduced in countries in the global south to promote biomethane for transportation and circular nutrient recovery for agriculture. Such an approach will require substantial investment in end-use infrastructure, and a consistent and coherent policy framework, with a shared ambition between multiple actors and sectors of the economy. In many LMICs, there are top-level policy frameworks, but the supporting policies and operational guidelines needed for implementation are missing or insufficient. In this respect, Xue et al. (2020) recommend multiple policies derived from global practices. Examples of such policies include supervisory policies to monitor and constrain ineffective plant operation; subsidy management policies to ensure targeted and staged support instead of one-time payment; environment protection policies to preserve the environment and ensure low-carbon development; innovation policies to promote technological and operational innovation through research and development; information policies to enable and widen communication through data, networks, knowledge exchange, and real-time monitoring. These policies can be adapted locally, considering contextual differences. Box 2 highlights some examples of policy coherence and incoherence in the biogas sector.

Box 2: Examples of policy coherence (+) or incoherence (-) in the biogas sector.

+ Incentivizing schemes such as feed-in tariffs, tax discounts, and targeted remuneration/premium for renewable energy technologies, including biogas.

+ Subsidies or tax discounts for decentralized electricity generation using biogas.

+ National policies that prohibit open dumping and landfilling of OFMSW and encourage RRR strategies for solid waste management.

+ Policies that promote biogas as a clean development mechanism and set annual decarbonization goals for fossil displacement.

+ Policies that promote the use of biomethane for transport, setting mandatory minimum percentage of biomethane that must be used in vehicles.

+ Policies that promote the use of biomethane for heat and/or electricity generation, setting a mandatory percentage of biomethane that must be injected into the gas grid.

+ Policy goals that promote nutrient recycling and biogas technologies in a circular economy.

+ Consistent policy push for waste management.

+ Policies that promote market-based mechanisms and sector coordination and collaboration.

– Policies that regulate the production of biogas from narrow feedstocks (e.g., biogas from energy crops), or exclude waste streams such as municipal solid wastes and sanitary wastes.

– Lack of direct subsidies for biogas plants while fossil alternatives are incentivized.

– Policies that encourage monopoly of gas networks and infrastructure.

– Lack of financial incentives or poor taxation for biogas use in transport, heat, and electricity sectors.

– Regulatory inconsistencies in the use of digestate from biogas plants as fertilizer.

– Policies that promote alternative use of manure for fertilizer and selective application of digestate.

– Feed-in-tariff/tax subsidy that primarily focuses on the use of biogas for renewable energy, or excludes other sector engagement.

– Frequent change in government policies, incentives or subsidies, which creates uncertainty and discourages long-term investment.

– Conflicting policies, e.g., renewable energy policies that conflict with waste management or agricultural practices and lead to suboptimal outcomes.

5.3. Well-Functioning Markets and a Robust Supply Chain

A stable and growing market demand is crucial for wide-scale implementation of medium- to large-scale biogas plants. A reliable market ensures a consistent revenue stream for biogas producers, making the projects financially sustainable in the long term. A robust market also instills investor confidence and thus can help attract funding for project development. Therefore, government policies that support market development and a strong supply chain are essential. Studies by Clemens et al. (2018) revealed that inadequate supply chains for the construction, operation, and maintenance of biogas equipment are a key reason for the prevalence of nonfunctioning biodigesters in the global south, particularly in Africa. Many digesters are imported into the region with parts and know-how that are not locally available or accessible. For many biogas operators, maintaining equipment is challenging due to a lack of spare parts. An example of this is the import of expensive double burner stoves from China to countries like Kenya and Tanzania although alternative kerosene stoves are cheaper and locally available. So, there is a need for system integration and close collaboration between sectors of the economy to ensure that operational constraints and supply chain risks are minimized (Namugenyi et al. 2022; Yue et al. 2022). This might take the following forms: Networking local and associated industries for equipment manufacturing, installation, and maintenance services; enabling training and capacity-building within the local community to maintain operational and maintenance supply chains; creating networks and supporting collaboration between farmers' groups to facilitate local knowledge exchange; and integrating agricultural systems such as crop-livestock farming to enable biogas production and use. The temporal and spatial distribution of biomass feedstock and infrastructure can also contain supply chain risks arising from seasonality, remote location of farms, and climate impacts of prolonged droughts and heat waves on agricultural yields (Martinát et al. 2016). Reduced manure availability due to poor animal feed may have a substantial effect on biogas yield. Furthermore, in certain countries, there are regulatory requirements to store digestates for a period before it can be applied on agricultural land. In the absence of storage facilities, such requirements may cause operational constraints. In this respect, integrating farm waste management and developing communal facilities such as waste processing and storage facilities can facilitate year-round operation (Lybæk 2014). Clemens et al. (2018) describe SNV's biogas sector development model that worked in Asia for large-scale dissemination of biogas plants, driven by "user-satisfaction and product credibility". The model relies on a coordinated effort to balance market forces and quality management by building a credible supply chain, new markets, and demand for biogas, and an enabling policy environment. This needed outreach support programs and education campaigns because of low market demand resulting from social barriers and cultural norms. Therefore, it is crucial to increase public awareness and understanding of the benefits of biogas through educational initiatives and implementation of biogas systems.

5.4. Clear Guidelines and Standardization of the Biogas Industry

Reviewing the biogas industry in China, Raha et al. (2014), Song et al. (2014), Wang et al. (2020), and Zhou et al. (2021) showed that the sector faced several challenges between the 1970s and 2000s, including poor quality of digester installation and operation, which led to a progressive slowing of technology adoption. However, an upward trajectory was achieved when standardized and efficient biogas digesters were developed, and national guidelines and standards were provided. Examples of work done toward standardization include the institution of a public limited company to mass develop biogas digesters and the establishment of specialized biogas research institutes to address sectoral challenges. Policies were developed for uniform construction and operation with emphasis on the quality of construction and management of digesters. There was a national effort to repair or reinstall previously built defective digesters. More importantly, a series of policies, regulations, and laws were developed to promote proper management of biogas digesters. This was accompanied by sets of national, industrial, provincial/local, association- and enterprise-level benchmarks such as standards for plant construction and production, diversified end-use purposes for digestates, and specifications for safe management of biogas projects. These various specializations and standardizations enabled the expansion of household biogas digesters from under 10 million in 2000 to over 40 million in 2017 and the rapid expansion of medium- and large-scale biogas plants, in addition to financial incentives, subsidies, and regulatory frameworks for the sector.

Such efforts are required across the LMICs to reduce poor design and installation of digesters and system failures associated with biogas plants. To ensure safe and effective implementation, it is necessary to establish or adapt national biogas standards and develop comprehensive guidelines that cover raw material management, biogas utilization, and safe use of digestates. These guidelines should also include licensing procedures and periodic environment audits. Monitoring and evaluation are mandatory to ensure compliance with environmental, safety, and health regulations. Training and public awareness campaigns and educational programs are crucial to enhance the capacity and engagement of various stakeholders. Scientific support is critical for optimizing biogas plants, contextualizing projects, and ensuring the adoption of the best environmental practices and best available techniques. This support can be achieved through technology transfer, scientific research, and research and development.

5.5. Enabling Market-based Instruments and Fiscal Mechanisms

Combining market-based instruments and fiscal mechanisms can create conditions conducive to the economic development of the biogas sector. The key lies in assessing the economic feasibility of various biogas business models and designing incentive mechanisms to support them. Some examples of effective incentives cited in the literature for the rapid expansion of medium- and large-scale biogas plants include tax breaks, free consultation, reduced tariffs, and tax exemptions (Pablo-Romero et al. 2017; Clemens et al. 2018; Xue et al. 2020). There are also several cases in countries like China (Zheng et al. 2020; Zhao et al. 2023), Demark (Pablo-Romero et al. 2017), and Germany (Thrän et al. 2020) of using feed-in tariffs and renewable energy credits to spark the biogas sector. These market-based and finance-based instruments were in the form of fixed-payment and tradeable certificates. Other risk mitigation instruments and revenue-sharing mechanisms include the issuance of green bonds and carbon credits through voluntary carbon markets to minimize financial or investment risks and encourage private investment and long-term partnerships in biogas projects (Sawale et al. 2020; Wang et al. 2016).

To enhance economic viability and maximize impact, targeting specific segments of the biogas value chain may be necessary to fully realize the potential of biogas solutions. Government incentive programs can be impact-targeted, considering the commercial viability of biogas within specific economic sectors. For instance, if feed-in tariffs for biogas electricity are not feasible due to infrastructure limitations, biogas generation and utilization may still be economically viable for on-site consumption. Industries that generate significant biowaste, such as breweries, sugar producers, and livestock agribusinesses, including pig and poultry farms, can be targeted for fiscal mechanisms to encourage participation in medium- and large-scale biogas plant development (Suwanasri et al. 2015; Saha et al. 2022). A supportive market-based business model and a regulatory framework that encourages private partnerships and the growth of the biogas industry should be designed to address bottlenecks throughout the biogas value chain (Buysman and Mol 2013; Clemens et al. 2018; Namugenyi et al. 2022). This includes clear permitting processes, standardized contracts, and transparent mechanisms. By making such arrangements, governments can effectively foster biogas entrepreneurship, thereby driving economic growth, job creation, environmental risk mitigation, and a transition toward a low-carbon economy. Marketing campaigns, technical assistance, and educational programs can be financially supported or incentivized, e.g., training programs and capacity-building initiatives to encourage support and investment in biogas initiatives. Box 3 highlights an example of market-based fiscal instruments for biogas sector development.

Box 3: Market-based instruments in the German biogas sector.

According to Thrän et al. (2020), the biogas sector in Germany has gone through four phases of market development: (1) Introduction; (2) expansion; (3) maturing; and (4) stagnation. In the introductory phase (1990-1999), there was almost no market for biogas. To enable the formation of a biogas market, the government in 1990 introduced a feed-in tariff that guaranteed a fixed remuneration to renewable electricity producers, which encouraged farmers to operate biogas plants with combined heat and power plants. This led to an increase in the number of biogas plants from around 100 in 1990 to 850 in 1999 (Figure 6). In 2000, the feed-in tariff was enabled by the Renewable Energy Act (REA), which sought to reduce GHG emissions by prioritizing electricity from renewable sources over conventionally generated electricity. A remuneration period of 20 years was set, and the size of the financial incentives varied among different renewable energy sources. Changes were made to support electricity production from biomass, including specific remuneration for energy crops and additional remuneration for innovative technologies, including upgrading biogas to biomethane. Between 2000 and 2003, the number of biogas plants increased from 850 to 1,750, with the average installed capacity increasing from 50 MW to almost 400 MW. Between 2004 and 2008, biogas plants almost doubled to nearly 4,000. In 2009, the REA was amended to include changes such as reduced subsidy rates for solar photovoltaic systems, which favored biogas installations. Various premiums and bonuses were also made available for renewable resources, increasing the use of manure, the proportion of utilized heat from biogas, and the use of bio-waste for biogas production. These incentives significantly increased the number of energy plants, expanding the number of biogas units to about 3,300. In 2014, the REA was amended again to expand market-based mechanisms. Direct marketing became mandatory for the larger renewable systems. The support for energy crops was removed with the focus shifting to using residual materials for biogas production. This allowed for better cost control and decreased the use of monoculture feedstock for biogas. The number of biogas installations was reduced, leading to about 500 new plants between 2014 and 2016. Since 2017, incentives for biomass plants have been paid out in a competitive tendering process with a view to phase out government support. Participation in the tendering process is mandatory for biomass plants of more than 150 kW. Financial support is only paid for the power produced that relates to the rated power of the installed capacity. Small biomass plants of <150 kW could receive a fixed premium of EUR 0.1332/kWh. These new approaches reduced new plant installations and consolidated the market for biogas technologies.

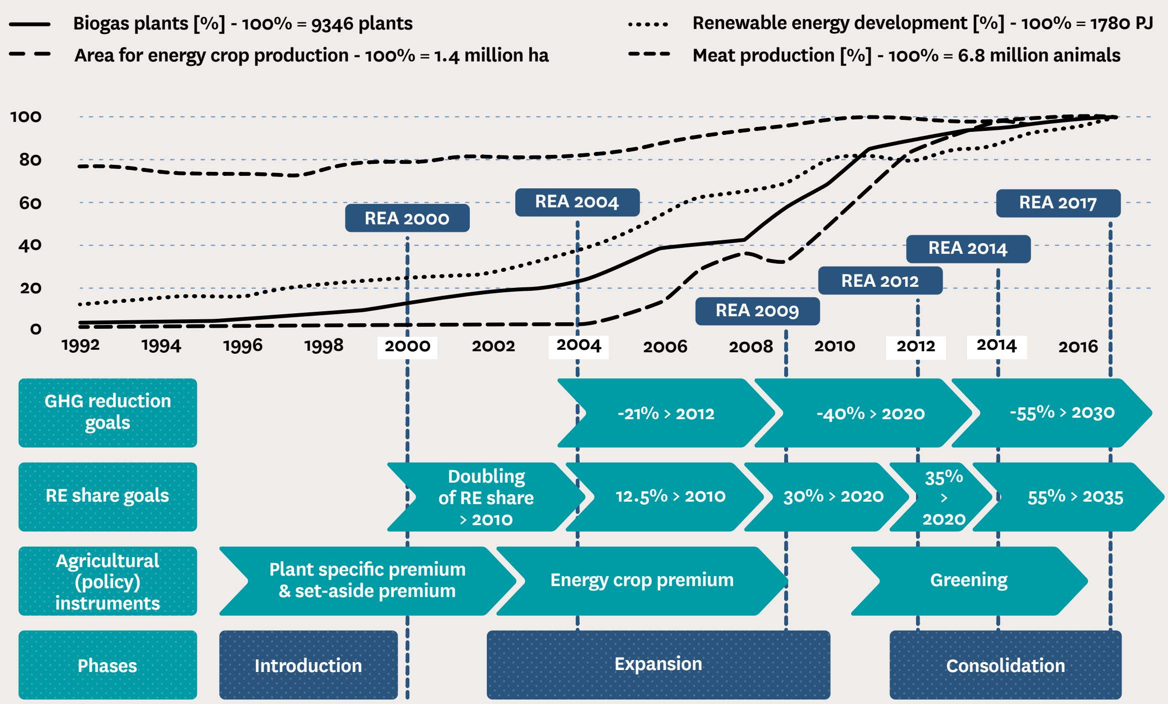

FIGURE 6. Phases of market and legislative development in the German biogas sector.

Source: Thrän et al. (2020).

5.6. Community Engagement, Sensitization, and Capacity-building

Addressing sociological barriers to wide-scale implementation of medium- to large-scale biogas plants involves understanding social, economic, cultural, and behavioral factors affecting widespread adoption and success of biogas projects. This can only be achieved when local communities are involved and engaged early in planning, decision-making, and implementing biogas programs and initiatives (Bourdin et al. 2020). For large-scale development of biogas technologies, it is imperative that social impact assessments are carried out and measures are taken to mitigate risks and impacts on communities (Fedorova and Pongrácz 2019). As highlighted earlier, it is important that vulnerable groups, including women and youth, are actively involved in decision-making processes and provided with enhanced opportunities or access to benefits (Mancini and Raggi 2022). Local leaders and influencers should be engaged to gain community trust and support. Community engagement can also take the form of inclusive business models where local people, entrepreneurs, and businesses are involved in the value chain of feedstock supply, biogas production and use, and related operational and maintenance requirements. This will require capacity-building, awareness campaigns, and training programs to ensure local communities understand the costs and benefits of biogas technologies. This approach will also provide opportunities to address any misconceptions or concerns. Adoption of biogas technology can also be encouraged by advocating for policies that support its integration. These policies may include financial incentives and regulatory frameworks, as well as government backing for community-led initiatives. Trust can further be built by fostering long-term community relationships and establishing mechanisms for ongoing communication and feedback (Kabir et al. 2013; Pandey and Sharma 2021; Mancini and Raggi 2022).

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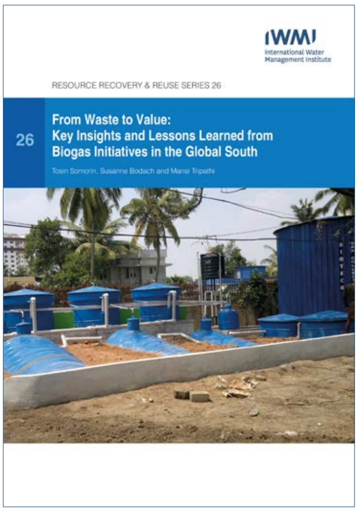

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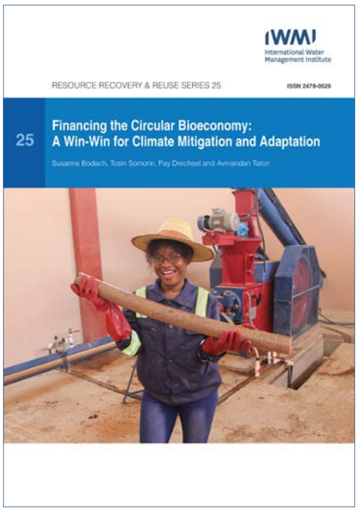

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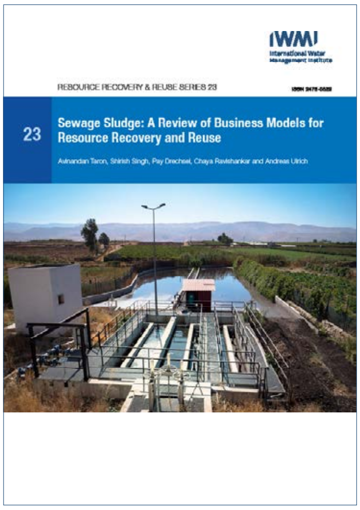

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International Water Management Institute (IWMI)
Headquarters
127 Sunil Mawatha, Pelawatte,
Battaramulla, Sri Lanka
Mailing address:
P. O. Box 2075, Colombo, Sri Lanka
Tel: +94 11 2880000
Fax: +94 11 2786854
Email: iwmi@cgiar.org
www.iwmi.org

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