Chapter

Small-Size Biogas Technology Applications for Rural Areas in the Context of Developing Countries

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Abstract

The world's rural population surpasses the three billion people mainly located in Africa and Asia; roughly half the global population lives in the countryside. Access to modern fuels is a challenge for rural people compared to their urban counterparts, which can easily access infrastructures and commercial energy. In developing countries rural populations commonly depend on traditional biomass for cooking and heating. A key strategy in tackling the energy needs of those rural populations is to advance their energy ladder from the inefficient, traditional domestic burn of biomass, organic waste, and animal manure. Governments and non-governmental institutions have supported small biogas digesters in rural areas, mainly in Asia, South America, and Africa, over the last 50 years. This chapter reviews the literature to offer an overview of experimental and theoretical evidence regarding the characteristics of design, construction material, feedstock, and operation parameters that made anaerobic digestion in small digesters a valuable source. Small-scale rural biogas digesters can generate environmental, health, and social benefits to rural areas with a net positive impact on energy access. Remarkable improvement in living standards was achieved with small inputs of the methane, produced via anaerobic digestion; however, challenges associated with lack of technical skills, awareness, and education remain and obstruct biogas' full potential in rural areas, mainly in developing countries.

Keywords: small-scale biogas installations, household biodigesters, rural livelihood, biogas in developing countries, energy access

1. Introduction

Anaerobic digestion is a technology that converts waste into energy. The produced biogas is considered as the primary energy output. The percentage of methane in the biogas is responsible for its calorific value, which is generally considered high [1]. Biogas can substitute oil, coal, and natural gas. Biogas can also be upgraded and directly used in natural gas pipelines and vehicles. The exploitation of fossil fuels and natural resources has increased greenhouse gas (GHG) emissions, deforestation, infertility of land, consumption, and water pollution. Biogas as a source of energy may help to mitigate those problems and reduce global warming. Moreover, using anaerobic fermentation to convert organic waste into fuel has many advantages over the use of crops to generate biofuels: it limits land use, food scarcity, and biodiversity damage. Thus, biogas represents an ethical choice for energy production [2]. In terms of net energy generation, the methane from anaerobic digestion is considered competitive regarding efficiency and costs compared to other biomass energies [3], and it is better from an ecological point of view [4].

Those benefits are already attributed to anaerobic digestion and biogas technology worldwide; however, the contribution of small-scale biogas installations to rural areas in developing countries has a wealthier meaning, and this chapter is aimed to disclose and discuss such value.

The design of biogas technology varies depending on the country, climatic conditions, and the feedstock availability; moreover, it depends on the policy regulations such as waste and energy programs and energy accessibility and affordability. Thus, biogas production may vary from different ranging set-ups, from backyard systems to large industrial plants. In developing countries, the domestic small-scale biogas installations, also called household anaerobic digesters, are the most diffused systems in the rural areas [5]. Those systems volume generally ranges up to 10 m^3 [6]. The digester size is limited by the available feedstock volume originated by the household and easily accessible; the most common feedstocks are manure from animal husbandries, food waste, small-agriculture waste, and sewage sludge. The household systems represent an effective strategy to enhance rural household life quality because it simultaneously advances sanitation and rural ecology and increases energy availability and incomes from the small agricultural activities [7]. The most common energy use of household biogas is for cooking and lighting [8]. Those systems have been successfully employed worldwide with governments and institutions' involvement, supporting household biogas' diffusion throughout subsidy schemes and programs of planning, design, building, and maintenance [9].

The chapter aims to offer an overview to the whole scientific community, to those already interested in biogas technologies but not expressly focused on developing countries and those who started to face the topic. It seems essential to attract new interest in biogas technology from practitioners involved in energy poverty and sustainable development for the Global South, the chapter is also directed to them.

2. Methodology

An overall evaluation of recent literature is used to compare relevant cases that disclose theoretical and practical assessments of small-scale biogas installations in rural areas. The literature review included only publications focused on developing economies; thus, papers were selected to achieve insights on the recent and current status of small-size biogas installations in such contexts. The information gathered is summarized here as principal aspects, designs, materials, and operations as they are applied to the most diffused small-scale and household installations in rural areas. Moreover, the literature data are compared to extract and discuss the relevance that small-biogas technology has for impoverished communities and the prevailing barriers that still slow down, or even prevent, biogas technology diffusion.

3. Rural areas in developing countries: defining the context

The world's rural population has been growing slowly since 1950. There are 3.4 billion people who live in rural areas around the world, 90% of them live in Africa and Asia. India (893 million) and China (578 million) represent 43% of the world's rural population. As the rural population worldwide became more sedentary and grew in population and density, the related environmental and public health problems increased. The population growth determined an increase of consumption needs, and several effects are due to such increased demands. The more prevailing demand is the need for food that can be met through intensification and extensification of agricultural land use; these two responses to the increased food demand are often led by the lack of technological innovation and efficient practices. Indeed, if the land is available, the land extensification is more likely to happen; depending on geographical area, communities may cut trees in lowland forest, use highland slopes in high mountainous regions, or root out brushes in semi-arid zones. Thus, in the absence of environmental controls and adequate rural policies, as generally occurred in the past, the consequences have been deforestation, soil degradation, and desertification in areas already marked by poverty. The population growth determines an increase in energy demand for cooking and heating. In developing countries fuelwood is the cheapest and primary source of energy for cooking and heating. If fuelwood is available in the vicinity, local deforestation results, otherwise deforestation occurs elsewhere also at a long distance from the community [10]. Besides deforestation, which represents an urgent issue in the current climate change era [7], fuelwood's use creates other concerns that need attention. In terms of environmental concern, the diffused utilization of inefficient biomass source contributes to the greenhouse gas emissions [11]. Indeed, biomass as wood and charcoal, both used in poor rural areas, is not sustainable, and when it is partly burnt, it causes emissions that contribute to global warming [12]. As a health concern, because of the use of wood stoves by the rural households, a high level of exposure to Respirable Suspended Particulate Matter (RSPM) from the fuelwood stoves smoke generates health hazards mainly for women and children [13]. From the perspective of social-economic aspects, the women and children are the main fuelwood gatherers (even from long distance), and the fuelwood is collected at the expense of their labor, time, and drudgery [14], and it withdraws them from opportunities of education and incomes.

In developing countries, the rural areas suffer more than urban clusters from lack of basic infrastructure with low access rates to clean water, household sanitation [15], and waste management [16], which determine high public health risk, which is exacerbated by the continuous growth of population and density. The absence of such infrastructures drives rural communities toward practices that negatively affect their surrounding with contamination and pollution of land, water, and air due to unmanaged organic waste from the household and livestock [17, 18]. Practices of burning organic waste as animal dung and crop residues represent how rural communities meet their cooking and heating needs, although it is inefficient and detrimental for the health [19].

Rural areas also suffer from the limited or absent electricity supply and distribution infrastructures, so rural populations have low access to electricity. It was estimated that 770 million people in 2019 were without electricity access; in Africa in the year 2020 there were 592 milion people without electricity access, and the Sub-Saharan represents the region where the access deficit is higher [20]. Such a struggle in energy access drives rural populations to rely on traditional biomass resources or become dependent on imported fossil fuel derivates. However, as already described, these resources have negative impacts on health and the environment and weaken those economies which are already fragile [21].

4. Developing countries: small-scale biogas programs for rural areas

The attention to small-scale biogas technologies has increased in the last decades globally, with fast development and diffusion in rural areas in Asia, Africa, and Latin America [6]. The mass dissemination was dependent on central government programs and long-term political support [22]. Between 1970 and 1985, China established a program for promoting and facilitating the installation of biogas in every rural household; the program brought the installation of 4.7 million household digesters by the end of 1988 [23]. A further increase was observed starting from the end of the 20th century, China registered more than 26 million biogas household installations in 2007 [5], and 43 million biogas users were counted in 2013 [24]. Since 1981, India had the National Project on Biogas Development (NPBD) with various training and development programs and financial support [25]. As a result of Governments' subsidies, over five million household biodigesters were installed in 2014 [26]. In Latin America, the introduction of biogas technologies for households was driven by the energy crisis in the 1970s when the Latin American Energy Commission (OLADE) prompted installations in several counties.

Moreover, the network Biodigesters in Latin America and the Caribbean (RedBioLAC) were created in 2009 to promote household, community, and farm-scale digesters in Latin America [27]. Bolivia stands out among the Countries involved in the network, with over 1000 domestic biogas digesters installed in 2014 [28]. Many other small scale biogas programs were implemented for developing rural areas [19, 29]. In Africa, over 44% increase in domestic digesters installed between 2011 and 2012, and about 60,000 digesters were in Burkina Faso, Ethiopia, Kenya, Tanzania, and Uganda in 2015 [30].

In many other cases, the success of biogas implementation was due to the combination of governmental support and non-profit organizations. Netherland Development Organization (SNV), based in Netherland, had supported national biogas programs impacting more than 2.9 million people in different continents [31].

5. Biogas production and potential in developing countries

The biogas energy supply is a valuable sector for the bioenergy industry. In 2017, 1.33 EJ of biogas was produced globally, representing 2% of the total biomass produced for energy purposes, but it has the potential to develop much more. Europe leads in biogas supply for more than 50% of the global supply, Asia follows it with 31%, and America with 14% [32].

Although the developing countries displayed more barriers for biogas application, some countries such as China [33], South Africa [34], Ghana, Rwanda, and Tanzania [35] produce biogas from large scale institutional plants using similar technology implemented in developed countries.

However, in developing countries, biogas is predominantly produced on a small and domestic scale. In China, the 43 million small-scale biogas installations contributed to generating, together with the large-scale plants, about 15 billion m^3 of biogas in 2014. It corresponds to 9 billion m^3 biomethane; moreover, the annual potential was calculated around 200–250 billion m^3 [28]. In Bangladesh, it was planned to build 100,000 small biogas systems by 2020, with an average c.a. 50 kW [36].

It is difficult for developing countries to find in the literature an exact number about the real contribution of small-scale biogas systems to the overall national renewable energy production. However, it should be noted that for the regions in which the energy access deficit is higher, domestic livestock biogas generation represents an enormous energy gain to move a step from the absolute energy poverty. For example, domestic biogas generation potential assessed in Nigeria showed an annual biogas projection of 138.7 X 10^6 m^3 from livestock, equivalent to 0.48 million barrels of crude oil [37].

6. Designs

6.1 Standard design systems

Biogas is a sustainable and affordable technology for rural areas where it is more convenient to adopt cheaper and simpler anaerobic systems to benefit from biogas production [38]. The household systems are low cost, simple to operate and maintain, and often constructed using local materials. The selection of the biogas systems depends on the construction, design skill, and material availability. Moreover, the design depends on the type of feedstock, climatic conditions, and geographical location. Generally, those systems do not have control instruments and heating apparatus and serve at room temperature (psychrophilic or mesophilic temperature) [5]. In tropical countries, digesters are underground to take advantage of geothermal energy; meanwhile, in mountainous regions, the systems have a reduced amount of gas to avoid discrepancies between the hot and cold season biogas production [39]. Traditionally, the generated biogas is used for cooking and lighting; however, biogas for electricity is increasing [40].

The most diffused systems in developing countries are fixed dome, floating drum, and plug flow type.

The fixed dome model is also called hydraulic digester (**Figure 1**) developed in China, where more than 45 million systems have been installed [6]; this type of system is also implemented in South Asia and Africa [31]. Typically, it consists of an underground digester and a dome-shaped roof. The digester's size depends on the amount of substrate available and the location; biodigesters are typically from 6 to 8 m^3 and operate in a semi-continuous mode. The new substrate is added once a day, while an equal amount of decanted mixed liquid is removed [5]. The digester is built from bricks, cement and reinforced by concrete. The system has one central part, the digester, dedicated to the fermentation and located at a deeper level, and above the ground level, there are two rectangular openings on each side, and they act as the inlet and outlet points for the digester. At the top of the dome-shaped roof, there is a pipe that is the biogas outlet. The digester is filled through the inlet, while the outlet also plays the hydraulic chamber's role. During the process, the biogas is produced in the digester, and it fills the upper part called the storage part (i.e., the dome). The pressure generated by the biogas presses the slurry from the digester into the inlet and outlet tanks. When the gas is released, the slurry flows back into the digester. Over the decades, this model has been improved and new

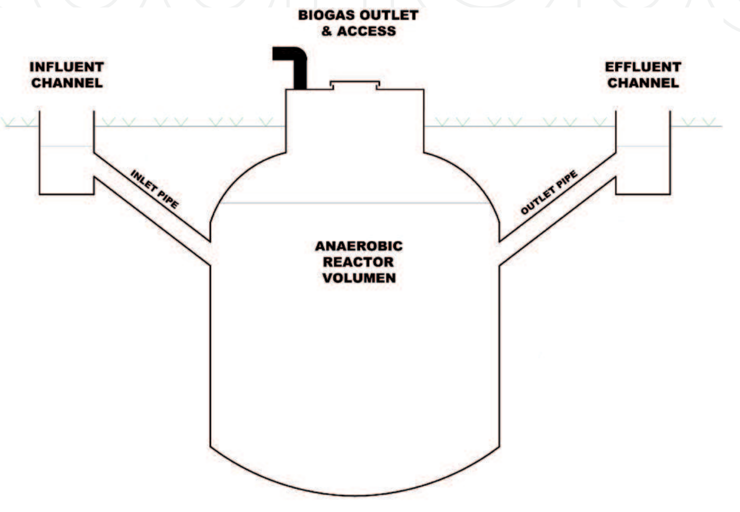

Figure 1.
Scheme of fixed dome digester model.

designs developed. In China, the digesters were modified with a hemispherical shape with a wall in the middle to increase the retention time and ensure a complete digestion process. Different fixed dome models were developed in India; first, the Janta model, a shallow system with a dome roof, has an inlet and an outlet above the dome equipped with the gas pipe. The Deenbandhu model, which is a modification of the Janta model, consists of two spheres; at the bottom, there is the fermentation unit, while at the top, there is the storage unit. In India, a low-cost model for light purposes was also designed with a vertical cylinder as a dome and with long inlet and outlet tubes [41]. In Pakistan, the French model digesters were installed; in this case, the digester is surrounded by a steel dome to prevent the loss in temperature [42]. Over the last years, alternative construction materials have been introduced to reduce labor costs and increase the system lifetime. Polymers and glass-fiber-reinforced plastics are used nowadays [43]. The fixed dome design is a reliable model with low maintenance and a long lifetime; for these reasons, it was implemented widely [31].

India developed the floating drum model (**Figure 2**); its design comprises a mobile inverted drum placed on the block digester with inlet and outlet connections through pipes located at the bottom. The digester is often partially underground. The drum acts as a reservoir; it can rise and fall along a guide pipe, depending on the produced biogas' volume. It produces biogas at constant pressure with variable volume. The weight of the drum applies the pressure required for the gas to flow through the pipeline. The digester generally is made of bricks and concrete. Meanwhile, the drum is made on metal or steel and coated with paints or bitumen to avoid corrosion, determining its lifespan. Galvanized metal and fiberglass-reinforced plastics represent a suitable alternative to standard steel [39].

The plug flow type or tubular model (**Figure 3**) was developed as portable model. This model is widespread, especially in South America [44]. It comprises a narrow and long tank (length: width equals to 5:1) inclined and partially buried in the ground, with the inlet and outlet over the ground and at the opposite side. Due to the inclination, the digestate flows toward the outlet; it is a two-phase system where acidogenesis and methanogenesis may be longitudinally separated. To keep

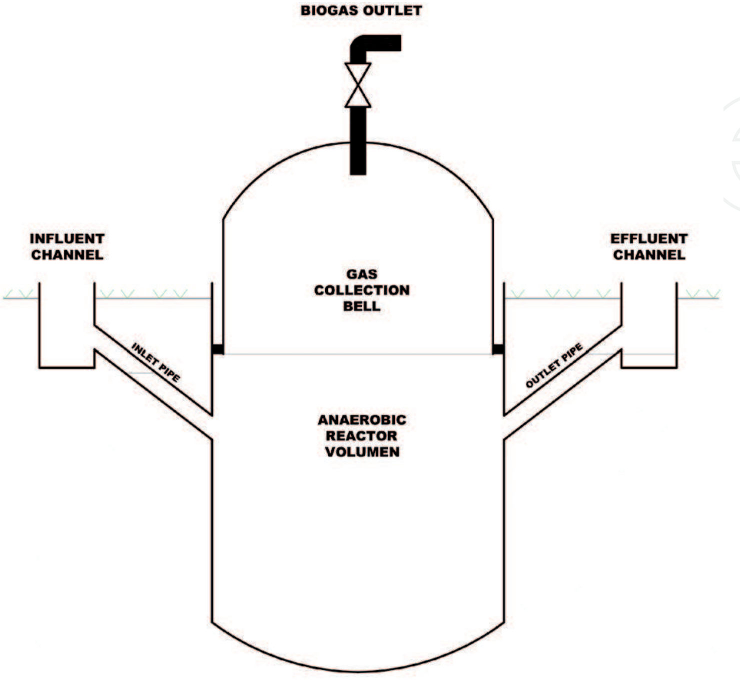

Figure 2.
Scheme of floating drum digester model.

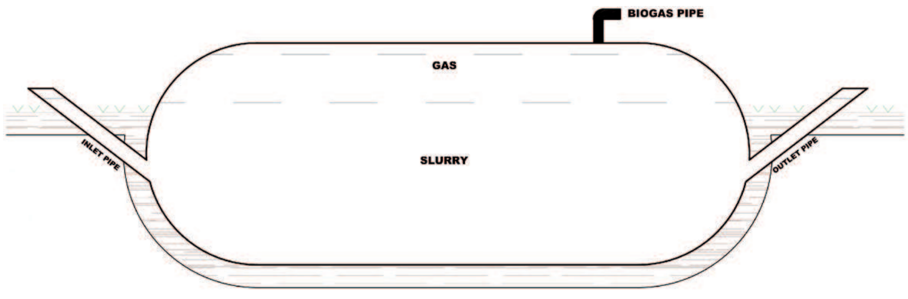

Figure 3.
Scheme of tubular digester model.

the process temperature adequate, the system needs insulation, and generally, a shed roof is placed on the top of the digester [39].

Comparing the tubular digester model with the fixed one, the fixed model can be fed with ratio manure: water 1:1, while tubular model 1:3, the former needs three times the amount of liquid [27]. Compared to the fixed dome, the plastic tubular digester has several advantages. It is a very low-cost model suitable to high altitude and low temperature, it is easy to transport and simple to install with lower investment costs, it needs less maintenance, and it is more environmentally friendly [45]. If the hard constructed models are compared from an economic point of view, for a capacity of 1–6 m^3, the cost of installation and the annual operational costs are the highest for floating model followed by fixed ones (i.e., Janta and Deenbandhu models). The floating type also has a longer payback period. With the increase of capacity, the cost of installation and the annual operational costs increase proportionally, and the payback period increases. It was shown that the Deenbandhu model (capacities from 1 to 6 m^3) is the cheapest model [46].

Regardless of the model, the household biogas systems may include auxiliary equipment to mix and handle the slurry and gas. The gas equipment may comprise pipes, valves, manometers [47].

Table 1 resumes the principal household biogas designs here described, including for each design, the advantages, the disadvantages, and the countries where it is mainly diffused.

The local conditions, biogas users' needs, waste, water, and land availability, are the criteria used to select the appropriate digester design in terms of volume and building materials [19]. Together with the different operational parameters, the design determines the biogas production and the quality of the digestate. As a decentralized energy resource, a poor design represents a particular limitation to users' adoption [50]. Moreover, sizing the digesters according to local needs and reducing the discrepancy between demand/production can avoid biogas' excessive production that often drives users to leak it into the surrounding environment purposely, and this causes a negative environmental impact [51].

6.2 Prefabricated and low-cost digesters

In recent years prefabricated systems were preferred for projects involving rural communities in developing countries. Those systems are also called "commercialized digesters" and often called "news digesters" because they involve new production materials, processes, and techniques. The main models generally used in developing countries are composite material digesters and bag digesters [9].

The bag-digester is also called balloon digester, tube digester, and it has a sealed soft plastic tubular structure. The long cylinder is generally made of polyvinyl chloride (PVC), polyethylene (PE) (**Figure 4**), or rubber. It was developed to address the construction problems with solid digesters (fixed and floating models).

Type of design	Modifications /models	Construction/Fabrication Materials	Advantages	Disadvantages	Geographical Diffusion	Ref.
Fixed dome digester	• Janta • Deenbandhu • French	• Bricks • Cement • Concrete • Polymers • Glass-fiber-reinforced plastics	• Low initial cost • long-life span (if appropriately built) • Less land required	• Requires high construction skills • Built with heavy materials • Gas leakage due to cracks	China India Nepal Uganda Tanzania	[43, 46, 48]
Floating drum digester		• Bricks and concrete for digester • Metal or Mild steel for drum • Reinforced fiber plastics • high-density polyethylene (HDPE)	• Easy construction • Visible storage volume • Gas at constant pressure	• High installation and operational costs • High payback. • Short life span (corrosion of drum) • High maintenance	India	[49]
Tubular	Pre-built and low-cost digester	• PE • PVC • HDPE • Glass fiber reinforced plastics	• Low cost • Easy transportation • Easy installation • Low maintenance	• Short life span • Requires insulation in a cold climate • Requires a high amount of water • Low gas pressure	South America Africa South Asia	[39]

Table 1.
Principal household designs used in developing countries (authors adaptation from literature sources).

Figure 4.
Example of low-cost PE- digester installation in South America. Image courtesy: Shikun Cheng.

Some Authors consider the bag digesters and the plug flow digesters different types, but actually, they are similar. In such a system, the biogas production is between 0.1 and 0.32 m^3 biogas/ m^3 digester/day, it equals the yield of traditional digesters used in India [52]. The bag-digester is more suitable in rural areas where the day temperature is above 20°C. This system has been widely applied in South and Central America [53], and at least 1 million low-cost PE plastic were installed in Vietnam with the Ministry of Agriculture and Rural Development. This system needs only two people for installation, and it can be easily transported, and for this reason, it was widely adopted for remote areas [9].

The composite material digesters are relatively new, originated in China, and well developed in East Asia countries [54]. The reinforced fiber plastic digesters represent a type of composite material digesters, and they can be manufactured through processes of resin transfer molding, sheet molding, and filament winding and they can also be built by hand (**Figure 5**). Such digesters are lightweight. Therefore, they can be easily transported and removed. They have long-term durability, good corrosion resistance to acid, high productivity, and high gas pressure (depending on the tightness). Several modified plastic digesters are also commercially available, and every model allows facile transportation. They are particularly suitable in rural

Figure 5.
Hand fabrication of composite material digester model in China. Image courtesy: Shikun Cheng.

Figure 6.
Commercial water tank (composite material digester) in Cambodia. Image courtesy: Shikun Cheng.

Figure 7.
Compact, high-rate digester for kitchen organic waste disposal. Image courtesy: Shikun Cheng.

Figure 8.
Typical portable digester for kitchen and green waste in Malaysia. Image courtesy: Shikun Cheng.

areas subject to reconstruction due to rural and land reform policy. Examples are represented by water tanks (**Figure 6**) and compact high-rate digesters (**Figure 7** and **Figure 8**) designed for kitchen and garden waste disposal [9].

7. Materials

As already mentioned in the design's description, the construction may involve different building materials. For household systems, bricks are essential material for fabricating of the digester chamber for both fixed and floating models. Generally, high-quality bricks should be used in the fabrication; however, clinker bricks are the most suitable ones because of their properties: low-cost, low moisture content, high resistivity, low thermal conductivity, appropriate thermal mass, weather resistance, fire-resistance, and tolerance to acidic pH. The concrete stones are used for building the block or the whole structure of the bricks/cement biogas digesters, they are the cheapest construction material, and they fit for the biogas purpose because of their tensile strength, durability, fire resistance, the thermal and conductive properties. The cement is also used for plastering purposes and building the concrete digester block and both the inlet and outlet. The most advantageous concrete used for the biodigesters is the Portland cement concrete (PCC), which has good density, compressive, flexural, and tensile strength. However, the use of these traditional materials brings challenges and holds disadvantages. Often the structures made with bricks, cement, and concrete, crack due to the structural stabilization and the fluctuation of temperature, usually resulting in leakages. High-quality materials and highly skilled labors are needed to minimize these problems, but those two aspects are often unavailable in developing countries. However, in recent years also alternative construction materials have been introduced like polyvinyl chloride (PVC), high-density polyethylene (HDPE), or glass fiber reinforced plastics (GRP). The PVC is used due to its low cost for building the inlet and outlet and for the digester chamber (in the case of plastic models) despite its short lifespan. Mild steel bars are usually used for the construction of the cover and the digester chamber. For the gas pipes, several different materials have been used as metal (steel or copper) and plastic (HDPE, PVC), and for the valves, generally, ball valves are used [55]. Because the biogas system's durability and cost are directly linked with construction materials, the pre-built and low-cost digesters are preferred for installations in developing countries [56]. Generally, off-site models are made with materials with specific characteristics such as glass fiber reinforced plastics (GRP), which have lower coefficient thermal conductivity, a longer operational life, and lower maintenance costs than the concrete models [54]. Several innovative design types were produced (already discussed in section 6.2), and they are commercially classified as fiber-reinforced plastic, soft plastic, and hard plastic digesters [9].

8. Influencing parameters

The process of anaerobic digestion requires the right conditions to have adequate biogas production; the most influencing parameters are temperature, organic waste composition, the moisture content, the mixing, and the hydraulic retention time (HRT) [57]. The generally suitable substrates for biogas production in rural areas are agricultural and livestock residues, organic fraction of solid domestic waste, and domestic sewage sludge (i.e., human excreta and wastewater). The biogas yield depends on the quality, amount, and supply rate (continuous or semi-continuous) of feed materials (**Table 2**). The biogas production can be directly measured by calculating the pressure of each digestor's headspace [58]. Several parameters can be used for monitoring the value of feedstocks, such as the Dry Matter (DM), the carbon-to-nitrogen ratio (C:N), Total Solids (TS), and the Volatile Solids (VS). Overall, animal manure is an ideal feedstock because of its high moisture and

Typical Feedstocks					
Manure	**Source of nutrient; high buffet capacity. Usually in co-digestion with straw.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Pig	Carbohydrates, proteins, lipids	3–8	70–80	3–10	0.25–0.50
Cattle	Carbohydrates, proteins, lipids	5–12	80	6–20	0.20–0.30
Poultry	Carbohydrates, proteins, lipids	10–30	80	3–10	0.35–0.60
Agriculture residues	**Source of cellulose, lignin, and starch. Need pre-digestion.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Straw	Carbohydrates, lipides	70–90	80–90	80–100	0.15–0.35
Grass		20–25	90	12–25	0.55
Organic household waste	**High variability of composition. Easily digestible. May inhibit the process for acidification.**				
Type	Organic content	DM%	VS% of DM	C:N ratio	Biogas yield [m^3/kg VS]
Fruit waste		15–20	75	15–20	0.25–50
Food residues		10	80	—	0.50–0.6

Table 2.
Common Feedstocks used in household digesters (author adaptation from literature sources).

volatile solids (VS) content and the buffering capacity, and also for its variety of microbial strains. The animal manures used in anaerobic digestion may vary according to the geographical area and local livestock practices [5, 30, 39].

The HRT always depends on temperature and substrate; however, there are no regulator instruments and no process of heating in the household systems that are generally installed in developing countries; thus, for each substrate, the optimum HRT should be found for best biogas yield because retention time affects the digestion process. The potential of cow dung, sheep, and pig manures in the plastic reactor was studied in Ethiopia, showing how at 25-28°C, a burnable gas with more than 60% of methane, was obtained from cow dung and sheep manure after 20 days of retention, while pig substrate needed more time [59]. In northern Brazil, the biogas production per kilogram of goat manure was ca. 54 L/kg in a modified floating model with a volume of 11.3 m^3 [60].

However, animal manure can make digestion slow because of its low content of carbohydrates [21], and it can generate a high concentration of ammonia, which is unfavorable for methanogens [61]. Mixing manure with other organic waste can create the optimum waste combination for the co-digestion process to improve the biomethane yield in terms of quality and quantity. Overall, the interaction within different waste streams directly determines the biogas yield [62]. In the co-digestion, the mixture of animal manure with an organic fraction rich in carbohydrates and low in ammonia has the remarkable ability to enhance biogas production. And vice versa, the agricultural residues with high VS, high fermentable constituents, and low moisture benefit from the co-digestion with animal manure or sludge due to their high content of ammonia. Compared with reactors supplied with manure alone, the volumetric methane production can increase up to 65% in reactors fed with waste and 30% VS of crop residues such as straw, sugar beet tops, and grass [63]. Co-digestion showed promising results using several mixtures of food waste and dairy manure at 35°C; a manure/food waste ratio of 52/48% produced methane yields 311 L/kg VS after 30 days of co-digestion. In comparison to raw manure, food waste contained higher VS (ca. 241 g/kg) it means higher energy content, which is desirable with regards to biogas energy production [58].

According to the different methanogenic microorganism's growth temperatures, working temperature ranges can be defined as psychrophilic (under 25°C), mesophilic (30-40°C), and thermophilic (50-60°C). Anaerobic digestion is a process that is sensitive to temperature [64]. Because simple systems as those used in rural areas in developing countries work at ambient temperature, the HRT should be selected considering local temperature conditions to give bacteria adequate time to transform feedstock into biogas. Depending on the climatic condition, the HRT varies from 10 to over 100 days [65]. At high altitude as Peruvian Andes (psychrophilic conditions), HRT from 60 to 90 days is needed [66]. In such high-altitude and cold climates, the temperature fluctuation also represents a problem for biogas production. In Andean villages, the low-cost tubular digesters were adapted by substituting the roof with a greenhouse. However, it was not always successful in maintaining a digester slurry temperature higher than the ambient temperature [64].

On the other hand, positives results were obtained from the modification of a floating drum model in Indian villages located at an altitude of 1600 to 2200 m, where the diurnal temperature fluctuates from −8 to 35°C during a year. Such fluctuation results in the reduction of gas production during winter by 23–37%. An improvement of the insulation kept proper operating temperature. That was achieved by enfolding the system inside a greenhouse or using hollow bricks for the construction or placing straw insulation around the digester, or adding hot water in the input feedstock material. These modifications allowed a continuous biogas production around 1.6 to 2.6 m^3/day during the whole year [67]. Solar-biogas hybrid systems where a solar collector provided the heating have been proposed for maintaining the right temperature for anaerobic bacteria to produce biogas [68].

In tropical regions with mesophilic conditions, the HRT may range from 20–60 days [19]. In Bangladesh, the rural dome-type digesters showed a retention time of about 40–50 days from a single feedstock such as cows' manure [29]. In Nigeria, the total biogas produced from poultry and cassava wastes was 1.5 m^3 after 42 days in a prototype polyethylene system of 1 m^3 at the ambient temperature of 33.6°C [69].

It is important to retain that while the temperature will affect the biogas, the feedstock security (or availability) influences the operation of the system [70]. For fueling a household stove twice per day in a family of five persons, it is required manure from one pig, five cows, or 130 chickens to have approximately 1.5 m^3 of biogas [6]. Gathering sufficient water and manure are among the limiting factors; in many parts of Sub-Saharan Africa, although the households possess adequate livestock, the grazing nature (nomadic, semi-nomadic, or free) may impede to gather manure to feed the biogas digesters [71]. A digester volume of 1.3 m^3/capita requires approximately 0.05 m^3/day of water for each cow and 0.01 m^3/day for each pig supplying manure to the digester. Such an amount of water can hardly be provided in areas of low water availability. In sub-Saharan countries, the water needed for digestion can be provided using recycled waters (gray water), such as domestic water, rainwater harvesting and aquaculture [72].

All rural small-scale and household digesters models require daily operation and maintenance. Everyday operations include the feeding, the handling of digestate, and the control of biogas outflow. Both brick and plastic tubular digesters are supplied with organic waste diluted with water in different proportions. The most challenging maintenance for the users comprises removing sludge from the digester, blocking possible cracks in the fixed digesters, and repairing damages in plastic systems [19]. Because installed digesters' functionality depends on continuous management and supervision of operation and maintenance, specific programs are often put in place to develop ownership and participation in using the biogas systems [73]. Sensitivity analyses demonstrated that small-sized digesters are more environmentally sustainable, if biogas leakage and release are avoided [51].

9. The relevance of small-scale biogas systems to regional development of rural areas in developing countries

The literature study discloses how small-scale biogas systems benefit the local family, village, and surrounding communities in rural areas in developing countries. Anaerobic digestion, even at the small-scale, represents an efficient waste treatment, and it offers a source of clean energy (biogas) suitable for cooking, heating, electricity generation, and a digestate with a high fertilizer value. It is a widespread opinion that anaerobic digestion implemented in poor rural areas may help in achieving several Sustainable Development Goals (SDGs), positive health impacts and sanitization, preservation of soil and water [74], reduction of greenhouses gas (GHG) emissions, gender empowerment and education [75], and accessible and affordable source of clean energy [76].

The use of biodigesters to treat human sludge and animal manure significantly improves the hygiene situation of rural areas that lack adequate infrastructure to collect and treat wastewater, unmanaged human and animal waste. The use of biodigesters can reduce infectious diseases such as diarrhea, cholera, and tuberculosis. Biodigesters also reduce the environmental impact (ecological, health, esthetic) of the spreading of waste in rural areas and reduce sewage danger percolating into the groundwater sources pumped for drinking water. Moreover, it contributes to the reduction of GHG emissions. It was calculated that processing the liquid and solid manure through anaerobic digestion reduces the potential impact from 4.4 kg carbon dioxide (CO_2) equivalents to 3.2 kg CO_2 equivalents if compared with traditional manure management [77].

Biodigesters represent a great alternative to the inefficient use of traditional biomass such as fuelwood, agricultural residues, and dried dung. Rural areas worldwide suffer from the loss of forest lands due to the illegal collection of firewood. The installation of biodigesters and the use of biogas can provide a substitute for firewood and save forests. Also, fuel oil and kerosene are widely used in rural areas for cooking and lighting purposes, especially in developing countries. Biogas is an excellent replacement for these fossil fuels and can save people hundreds of dollars every year. Besides that, countries with large amounts of rural areas are usually poor and oil-importing countries. The use of biogas can save those countries millions of dollars every year.

The use of biogas as a clean source of energy for cooking also includes important health benefits. It reduces exposure to indoor smoke and soot, reduces respiratory and eye diseases, reduces fatalities caused by carbon monoxide poisoning and offers a significant reduction of the RSPM in indoor environments.

Biogas use has many positive social outcomes on education and gender equality, and it generates employment opportunities for rural communities. The lack of enough lighting in rural areas in developing countries prevents students of all ages from having enough light to study or even be involved in any educational activities in the evenings. Biogas in gas lamps provide enough fuel for lighting and provide more study hours in the dark [78]. Moreover, in such poor areas, women are in charge of securing water and energy [67, 75, 79]. Having a biodigester at home will save women tens of hours of collecting firewood. This time can be used by women for other activities such as education and socializing. Also, burning biogas does not generate any particulate matter or soot that pollutes the houses, saving women cleaning time [21, 78]. Moreover, an increase in employment in rural areas was recognized as the positive impact of small-scale biogas installations. These news opportunities mainly involved women and professionals in education, environment, agriculture, and technical professions related to the building and maintenance of the systems.

The use of biodigesters reduces the use of chemical fertilizers. Along with the biogas, biodigester produces organic fertilizer rich in nutrients, such as nitrogen, potassium, and phosphorus. This organic fertilizer can replace commercial fertilizers and save farmers in rural areas thousands of dollars every year. Also, this liquid fertilizer can keep the use of water for irrigation. Thus, biodigesters maximize the valuable fertilizing properties of the recycled waste for agriculture; this benefit will lead and promote the local family's economic advancement.

10. Biogas serves to reduce energy poverty in developing countries

In some countries, rural people do not even have access to fossil oil and kerosene because of their price or shortage; those people are forced to meet their energy needs using traditional and inefficient resources. As described, such practices represent significant health, environmental, economic, and social issues for those communities. Within the context of sustainable development, nowadays, it is imperative to offer these disfavored regions access to clean, affordable, and renewable energy. Assisting people to transform the animal manure, crop residues, domestic waste into a more efficient energy carrier, such as biogas, provide clean and reliable energy, and conserve the local and global environment [21]. It is evident how biogas' decentralized production gives several opportunities for accelerating the transition to sustainable development and the circular economy with positive economic effects at the local-level livelihood [80]. Biogas is an energy source useful for people to meet their energy needs without using fossil fuel [8].

In Northern Brazil, a biogas volume of 1 m^3 from manure was equal to 0.75 L of gasoline [60]. Small-scale biodigesters produce around 2–4 m^3/day biogas, sufficient to meet the cooking lighting needs of a family [62]. The biogas potential in Colombia showed that 80% of propane, which is used the traditional fuel, could be replaced by biogas; results showed that a low-cost tubular digester in polyethylene with a total volume of 9.5 m^3 and feed with cattle produces enough biogas to supply cooking of five hours/day for five people [81]. In India, positive achievements were obtained using different design models simultaneously; it was possible to produce approximately 40.5 m^3 biogas/day and supply the community of 48 households that had cooking needs of 0.85 m^3/day each [82]. In Bangladesh, about eight head of cattle per household were needed to cover the need for cooking gas, electricity, and drinking water [83]. In Nepal, 0.33 m^3 of biogas fulfills the energy needs per capita per day [84]. In Israel, post-nomadic Bedouins families adopted a system of 7.5 m^3 fueled with goat manure and straw that provided biogas for cooking and for powering a little refrigerator [85]. In Bali approximately 30 m^3 biogas/month using cow manure can supply the energy need of a 5–6 people family size [86].

Small-size biogas technology embodies the opportunity to address the energy access issue for low-income developing countries [87]. Biogas digesters may reduce energy poverty [35, 88], and they provide clean energy for cooking and lighting for rural areas where energy infrastructures are missing [39].

11. Challenges of biogas systems in rural areas for communities in developing countries

Despite all of the benefits biodigesters have for rural communities, some biogas systems in rural areas do not meet the expectations due to technology, maintenance, and technical support. All those aspects induce a discontinuity of digester operation as documented for China, in the Guizhou Province, 62.03% of household biogas were continuously operating while 36.72% were discontinued [89]. In some other cases, the challenges represent the reasons for technology's abandonment [90]. This section summarizes the challenges biogas systems are facing in rural areas.

In cold rural areas, biogas system owners lack the right technology to maintain the thermal conditions for a high rate of biogas production [57]. The people in these areas face this challenge, especially in winters where energy need is higher than in other seasons. As described above, the household biogas digesters are made of bricks or concrete and built just under the ground surface where the digesters' temperature is very close to the ambient temperatures. Thus, without appropriate heating or hybrid technologies, the household biodigesters' efficiency remains low and unstable under these conditions. Design solutions have been developed to maintain the right temperature for biogas production, such as insulating the digesters or combining with other heating technology (i.e., solar water heaters). However, these solutions may cause a burden for people in rural areas.

The lack of technical knowledge and building capacity in rural areas is another critical factor that leads to low biogas production rates. People in rural areas lack access to formal education, awareness of environmental issues, agricultural techniques, and appropriate knowledge on how to run the biodigesters. In some countries, farmers get governmental financial supports to construct biogas systems. In many cases, this governmental support is not accompanied by technical support and safety measures to adequately manage the biodigesters [21, 26, 78, 91]. Also, the lack of knowledge about the ratio between the size of the biodigester and the volume of organic waste can lead to low biogas production rates and digestate pollution near the biodigester. That may cause odor emissions, eutrophication of surface water, and pollution of groundwater. As described below, only a rational design of the small-scale system, along with a proper build, continuous cleaning, and maintenance, affects the productivity and the environmental footprint of the system [51].

In general, rural areas are located in remote zones where it is difficult to reach and run educational programs and maintenance. Also, the lack of governmental follow-up and capacity building programs leads to poor maintenance and operation of the biogas plants.

The inadequate use of liquid fertilizer may attract flies and mosquitoes to the biodigester and cause a challenge for the biodigester users. Also, this may create adverse publicity of biogas plants among people.

Low or discontinuous biogas production due to improper operation of the biodigester, technical barriers, lack of feedstock (animal manure or food waste), and low level of awareness may lead to an inadequate supply of biogas. Thus, people in rural areas are discouraged from using the biodigesters on a daily or seasonal basis. It may lead to low adoption rates in rural areas and force people to switch to more reliable fuel sources.

12. Conclusion

The chapter presents the effective implementation of small biogas digesters in rural areas in developing countries. Small Biogas digesters represent a tool to achieve rural areas' sustainable development, giving access to clean and affordable renewable energy. The use of biodigesters in poor rural areas serves as an environmentally friendly way to reduce fossil fuels and traditional biomass and reduce indoor and outdoor air pollution. Also, the use of biogas can significantly reduce organic waste in poor rural areas. Design, construction materials, feedstock operational modes vary accordingly with the geographical location of biogas installation. The systems installed in rural areas are simple and mainly for domestic uses. The biogas yield can be controlled and increased by controlling the retention time and modulating feedstock composition in a co-digestion process using manure and other organic waste. Despite the potential and the wide range of benefits that rural areas can acquire from the small-biogas digesters, several potential problems limit the diffusion of small-scale anaerobic digesters in rural areas in developing countries. They include the lack of construction and maintenance skills, awareness of users, and the inadequacy of design to meet the actual biogas (energy) need. For biogas systems to succeed and be used in rural areas worldwide, governments should strengthen current policies and develop new policies and regulations to motivate people in rural areas to install biodigesters. These policies should focus on the comprehensive sustainability of the biogas systems. The policies should include incentives and procedures for constructing the biogas digesters and comprise tools to support the systems' management.

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Conflict of interest

The authors declare no conflict of interest.

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