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Review Article

Current Status and Future Prospects of Small-Scale Household Biodigesters in Sub-Saharan Africa

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Despite the age of the technology, sub-Saharan African (SSA) countries have numerous challenges that hinder biogas from being widely adopted. This review investigates the current gap between holistic use and the need for small-scale household biodigester adoption and effectiveness in rural and semiurban households of SSA. It reviews the present situation and potential of small-scale household digesters for sustainable future energy and biofertilizer use, with a focus on SSA. A literature survey was performed on small-scale household biogas digesters, and issues relating to the distribution, use, and implementation status with their implications on the future of small-scale household digesters in SSA were briefly reviewed. In recent years, the overall number of domestic biogas digesters installed across SSA countries has shown a significant increase due to the efforts of the National Domestic Biogas Programs such as the African Biogas Partnership Program with the Netherlands Development Organization and the Humanist Institute for Development Cooperation. However, based on an extensive literature review on small-scale household biodigesters in SSA, the study highlights that the success of biogas technology as a clean domestic cooking fuel has been relatively low. The findings of this review show that SSA countries still face a number of hurdles, the most significant of which can be boiled down to the need for technological advancement according to local context, social acceptance, and large initial investment costs. In order to overcome these obstacles and advance technological capability, social acceptance, financial benefits, and environmental impacts in order to improve its use and widespread dissemination as a renewable energy source, a highly effective organic fertilizer, and economic benefits for the betterment of SSA communities, more well-organized work and adequate research activities should be initiated and supported. The findings may be useful to researchers, practitioners, and policymakers who support/promote sustainable energy and waste management strategies in low-resource settings.

1. Introduction

Due to the expanding worldwide energy demand and increased efforts to replace fossil fuels with more sustainable alternatives, biomass is currently being produced on a large scale for use in the production of renewable energy [1]. Energy derived from fossil fuels, on the other hand, has a detrimental impact on the circumstance of natural environment by accelerating its degradation [2]; thus, utilizing first-generation biofuels (ethanol and biodiesel) is recommended [3–5]. Due to their higher consumption of solid biomass and petroleum products than other African countries, SSA countries have more difficulty reducing their greenhouse gas (GHG) emissions [6]. Anaerobic digestion (AD), which is significantly more sustainable by using locally accessible resources, has drawn a lot of interest and motivated researchers to create environmentally friendly and financially feasible alternatives [7–9]. In addition, Achinas et al. [10] reported that the high value of biofertilizer (compost) produced from waste enhanced AD technology and privileged the biogas economy. One of the most potential alternative, sustainable, and renewable energy sources of the future, on both small- and large-scale levels, is the utilization of agribiomass, which is essential for energy generation [11, 12].

In the developing world, small-scale biogas digesters are broadly and increasingly used to convert waste into valuable gas and may represent an economically viable technology, that simultaneously produces biogas and digestate as biofertilizer [13, 14]. Cost-effective energy production and utilizing bioenergy is the means to improve the living standard of developing countries [15]. Biogas is an alternative opportunity for households that have access to adequate and suitable organic substrates and having no adequate income to subscribe expensive energy sources. Between 2010 and 2018, the worldwide biogas industry has increased more than 90%, while further growth is still expected [16]. Approximately, 50 million biogas systems have been installed throughout the world to produce gas for cooking [17]. Across Asian countries alone, tens of millions of small-scale anaerobic digesters are used in households or on small farms and are in operation in countries like China, India, and Nepal [18, 19] and Vietnam [14, 20, 21] and parts of Southeast Asia [22]. In Europe also, the production of biogas reached 1.35×10^7 t in 2014. As reported by Achinas et al. [10], Germany is the pioneer country in global biogas production, with approximately 25% installed capacity as a result of the strong development of agricultural biogas plants on farms, and more than 8000 were in operation as of the end of 2014.

In Africa, the research and use of household biogas digesters has a long history. Whereas not as common as in Europe and Asia, household biogas digesters have been established in Africa since the 1950s (South Africa and Kenya). Many African countries showed a low dissemination strategy of domestic biogas and a low level of technological development. In SSA countries, the most broadly used biogas model is that of small-scale biogas digesters using household and domestic animal wastes. The majority of the literature relating to the utilization of biogas in Africa talks about its possible input to the interests of its community, environmental protection and economic progress, or the challenges for large-scale uptake of the technology [17, 23, 24].

Currently, more than 2.5 billion people need clean and safe cooking fuel at a global level. The Africa Biogas Partnership Program (ABPP) is a partnership between Hivos and SNV aiming at developing a sustainable domestic biogas sector by supporting the adoption of biodigesters in rural households in five African countries (Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso). In developing countries, most household energy is provided by traditional solid biomass resources such as firewood, charcoal, agricultural residues, and animal waste such as dung [25]. Cooking by such solid fuels is a main source of one of the world's biggest killers due to its high indoor concentrations of household air pollutants [26] and annually kills nearly 2 million people, out of which 600,000 deaths are in SSA alone and creates a lot of extra health problems.

Using biogas can replace some of the traditional fuels, and by doing so, it can contribute beyond only delivering a clean fuel. Also, unsustainable collection and inefficient utilization of these traditional fuels exhaust natural resources, damage the environment, contribute to climate change and hamper the empowerment of women and girls [26]. As reported by Tumwesige et al. [27], over 700 million people in the SSA rely on solid biomass fuels to meet cooking and heating energy needs, whereas Clemens et al. [17] reported that more than 95% of households use solid biomass fuels as a primary source of energy for cooking, particularly in rural areas. Nevertheless, access to fewer polluting fuels is limited for most of the population in SSA. To meet basic needs for cooking and lighting all over SSA, people tend to obtain their household energy primarily from traditional solid biomass fuels. In SSA, the consumption of firewood represents the largest source of energy and is the predominant source of biomass energy for most families [27–30]. Hence, the production of biogas via AD is an option for providing clean and sustainable cooking in developing countries, especially in rural regions for households that have access to sufficient, and suitable organic feedstock [17, 31, 32]. This technology has significant potential to meet Africa's energy requirements through amongst others simple installations in rural developing communities that could produce enough energy for cooking and heating and could be prolonged to community-based or commercial biogas generation efforts [33].

Therefore, this paper reviewed the use and implementation of small-scale biogas digesters with a focus on the situation in SSA countries; the review critically analyses the benefits and challenges of implementing biogas systems at a household scale for producing energy and digestate/fertilizer simultaneously, along with improving the environment and livelihood of the poor. It considers the record of the past and status of household digester technologies in most SSA countries, including the technological, economic, social, and environmental factors. The paper mainly reviewed the challenges in order to overcome and improve the use and implementation of the technology and its dissemination for energy and nutrient recovery purposes.

2. Overview on Status and Prospects of Biogas Technology in Sub-Saharan Africa

Biogas technology is one renewable resource that is assumed to have a substantial impact on SSA's capacity to address its energy and environmental issues. Household biogas was originally introduced roughly 40 years ago in a few African countries. But major participation did not start until later in 2008 [23]. Biogas is becoming more crucial and playing an important part in the energy sector. Numerous digesters have been installed in several SSA countries, using a variety of feedstock like animal manure and human wastes, crop residues, leftovers from slaughterhouses, municipal and industrial wastes, water hyacinth plants, and waste from commercial farms (such as manure from chicken and dairy farms) [23].

Biogas plants can generally be divided into small- and large-scale plants. Most often, the terms "mid-scale" or "medium-scale" are used in combination with either small-scale or large-scale. Several terms, primarily in rural areas, are used to denote small-scale biogas plants, including household, domestic, farm, decentralized, and community. Numerous small-scale biogas digesters have been installed throughout the SSA countries, but few of them are now in use due to poor technological quality. Biogas has the potential to minimize the importation of fossil fuels and inorganic fertilizers, boost national energy security, bring clean energy to remote and rural populations, and open up employment opportunities for young people in low-to-middle-income countries. Many international development organizations/agencies and country initiatives have provided free or inexpensive biogas installation to rural households in SSA, to support the adoption of biodigesters and appreciate a lot of its benefits. Cooking with biogas is technically feasible for 18.5 million households in 24 African countries, based on population density, fuelwood scarcity, livestock ownership, water availability, and climate conditions according to a study in 2007 conducted by the SNV and the International Institute of Tropical Agriculture [17]. ABPP had installed 57,000 biogas digesters by the end of 2016 in a number of SSA countries since the program began in 2009, and about 320,000 people have benefitted from the programs by June 2018 [27]. Schematic diagram of biogas operation is indicated in Figure 1. As a result, many prospective opportunities for attaining sustainable growth have opened up. SSA adopts fewer small-scale biogas digesters than other developing countries, even though there are significant potential benefits. Biogas technology has not been successfully applied as an economic or energy strategy in SSA up until now. Due to the campaigning efforts of numerous international organizations and foreign assistance agencies through their trips, conferences, and publications, small-scale biogas digesters have received increased attention in SSA.

Access to electricity is crucial for a country's economic success. On the other hand, many SSA countries continue to face significant developmental obstacles due to limited access to electricity. For instance, millions of people lack access to power in Africa. Sub-Saharan Africa is home to more than two-thirds of the world's population without access to electricity [34]. Other dimensions of socioeconomic development, such as income-generating activities, market output and revenues, household economics, population health, education, and social networks, are also shown to have a causal link with access to electricity and related factors [35]. Lack of access to electricity and clean cooking facilities are the two fundamentals that are necessary to meeting basic human needs [14]. SSA is also home to the largest number of countries with the lowest rates of electrification Table 1, and to meet their basic needs for lighting, heating, and cooking, the highest number of people is forced to depend on traditional biomass resources such as wood, animal, and agricultural wastes [36].

Additionally, the population expansion in the SSA is outpacing the rate at which people are moving away from solid biomass for cooking. By 2030, 823 million people in SSA are expected to be forced to use unimproved cook stoves that burn solid biomass, based on present trends. The struggle to secure modern energy access, for example, is made more difficult by this significant rise [37]. SSA has a household energy balance of approximately 85% provided by biomass fuels and fuelwood, compared to 25% in Latin America and 37% in Asia [27, 37]. If policies regarding energy access for developing countries, particularly in Africa, do not considerably change, it will be difficult to significantly reduce the number of people around the world who rely on polluting solid fuels and kerosene [38]. SSA has a wide range of sustainable feedstock sources, including forestry biomass, municipal solid waste, and agricultural waste. The non-sustainable extraction of fossil fuels and traditional biomass fuels has raised awareness of the existence of cutting-edge and renewable energy sources like biogas.

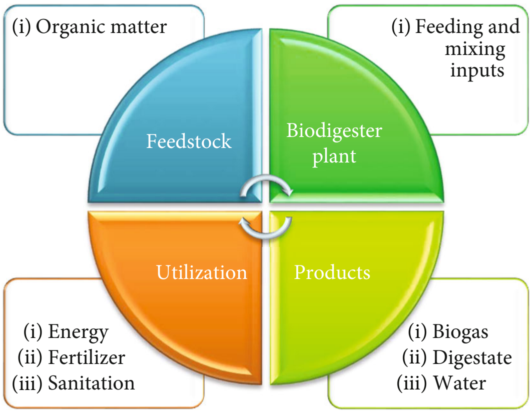

Figure 1: Schematic diagram of biogas operation.

Domestic biogas digesters have been introduced at different times in the various SSA countries that include South Africa and Kenya since the 1950s [27, 39], Ethiopia 1957 [40], Tanzania 1970s [41], and South Sudan 2001, and until now, biogas digesters have been installed in many SSA countries including Burundi, Botswana, Burkina Faso, Cote d'Ivoire, Ghana, Guinea, Lesotho, Namibia, Nigeria, Rwanda, Zimbabwe, and Uganda. Relatively, the majority of African countries showed a low level of technological development and dissemination strategy of domestic biogas. The overall quantity of domestic biodigesters installed in selected African countries is presented in Table 2, which shows a significant increase in domestic biogas digesters across SSA during recent years because of the efforts of the National Domestic Biogas Programs (NDBP) such as the ABPP with SNV and Hivos supports.

Energy use and demand in SSA are generally expected to continue to increase as growth occurs at a rate faster than that of developed nations [42]. There is a need for a consistent biogas technology coordinating structure and policy in many SSA countries, despite the daily increases in the price of traditional fuel and their growing demand for both technological and nontechnological components.

3. Anaerobic Digestion Technology and Process

Anaerobic digestion (AD) is historically one of the oldest processing technologies utilized by mankind. The AD is a biological and chemical degradation of organic matter with different species of bacteria operating in anaerobic mode [43]. Biogas is a generic term for gases generated from the anaerobic bacterial decomposition of organic material. The biogas composition is mainly influenced by the feedstock used for digestion, the microbial process itself, and the operation parameters of the anaerobic digester [44]. Biogas is primarily composed of methane (40–75%) and carbon dioxide (15–60%) and minor amounts of other gases including

Table 1: Access to electricity and clean fuels and technologies in 2021 [98].

	Sub-Saharan Africa	Middle East and North Africa	World
Population, total (billion)	1.18	0.486	7.89
Access to electricity (% of population)	50.6	97.3	91.4
Access to electricity, urban (% of urban population)	80.7	99.7	97.7
Access to electricity, rural (% of rural population)	30.4	93.3	84.5
Access to clean fuels and technologies for cooking (% of population)	19	96	71
Access to clean fuels and technologies for cooking, urban (% of urban population)	37.1	99.1	87
Access to clean fuels and technologies for cooking, rural (% of rural population)	6.8	90.9	51.2

Table 2: Number of household biogas digesters installed in selected African countries.

Country	Msibi and Kornelius [23, 24, 26, 28] and Surendra et al. [65]		IRENA [99]		Clemens et al. [17]		SNV [100]
	Year of initiation	Cumulative no. of domestic biogas plants installed up to 2012	Year of initiation	Household-scale biogas digester units in selected countries, 2014	Year of initiation	Cumulative no. of biogas plants reached up to 2017	Cumulative no. of biogas digesters installed up to 2021
Kenya	2009	6,749	—	14,110	2009	13,260	26,768
Uganda	2009	3,083		5,700	2009	7,588	9,019
Tanzania	2008	4,980		11,100	2009	6,441	
Ethiopia	2008	5,011		10,680			34,693
Burkina Faso	2009	2,013		5,460			15,019
Rwanda	2007	2,619		1,700			11,625
Cameroon	2009	159		300			
Benin	2010	42		110			249
Senegal	2010	334		—			
Zambia							5671

hydrogen sulfide (0.005–2%), nitrogen (0–2%), oxygen (0–1%), ammonia (<1%), carbon monoxide (<0.6%), siloxanes (0–0.2%), and halogenated hydrocarbons ($\text{VOC} < 0.6\%$) [45, 46]. Besides biogas, AD produces digested substrate usually named a digestate, a product that can be utilized as an agricultural fertilizer and soil conditioner because the nutrients that exist in the raw feedstock stay in it and are simple to get from crops after the digestion process [47].

Biogas via AD is an energy-efficient and environmentally friendly technology that has considerable advantages over other types of bioenergy technologies [48]. AD has gained increasing interest as a significant renewable energy source and biofertilizer, respectively, due to its ability to transform organic waste into energy-rich biogas and a plant nutrient-rich residue (digestate) [49–51]. AD has become a primary process for the treatment of agricultural wastes and food residues [52]. Any organic waste containing highly volatile organic matter can be digested to produce biogas, which contains methane as the main energy carrier [53]. The two main technologies available are mesophilic and thermophilic digestion. The main difference between these technologies is that for thermophilic AD, higher heat energy is demanded. This technology has a larger gas output capacity and higher methane gas content. Nevertheless, mesophilic AD is the most familiar system due to its more stable operation and lower operational expenses. Figure 2 shows the schematic representation of anaerobic digestion of biochemical process consisting of several stages. Major phases include hydrolysis, acid formation (acidogenesis), acetate (acetogenesis), and methane generation methanogenesis [54, 55].

3.1. Biochemical Reactions and Process of Anaerobic Digestion.

3.1. Biochemical Reactions and Process of Anaerobic Digestion. As presented in Figure 2 above, there are four key biological and chemical stages of AD. In the first step, the hydrolysis phase involves the use of enzymes that originate from anaerobic bacteria in the digester to decompose high-molecular-insoluble organic substances or the complex compounds of the starting material (such as carbohydrates, proteins, cellulose, and fats) into low-molecular-soluble substances (e.g., amino acids, sugars, and fatty acids). During the second phase, acidification (acidogenesis), through acid-forming bacteria, continues the decomposition process into simpler compounds such as organic acids (acetic, propionic, and butyric acid), carbon dioxide, and hydrogen, and small amounts of lactic acid and alcohols. In the third phase, the so-called acetic acid formation (acetogenesis),

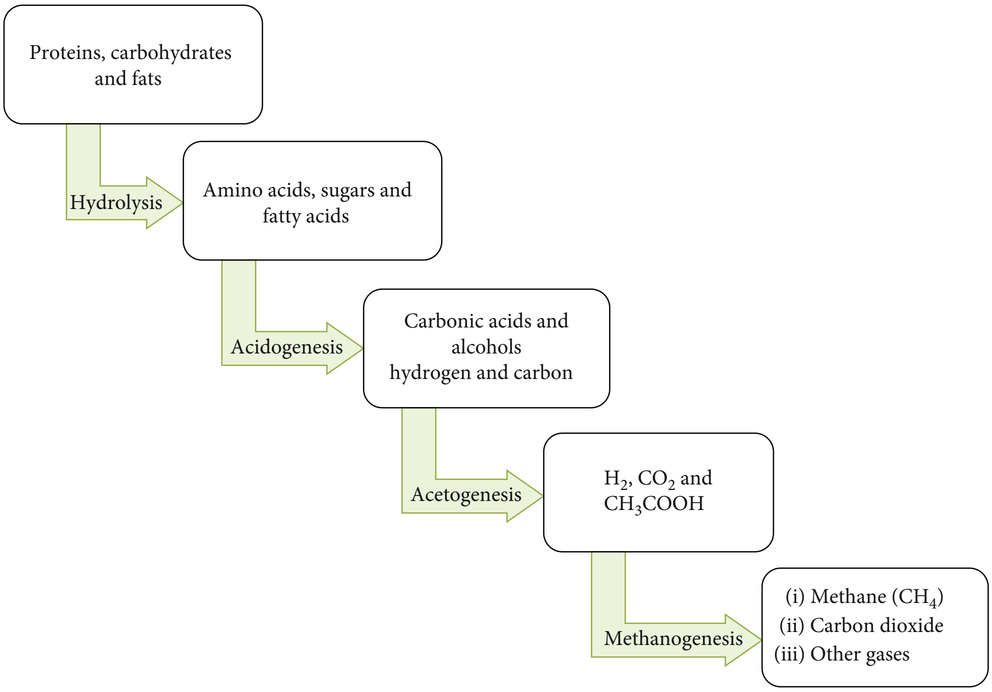

FIGURE 2: Schematic representation of anaerobic phases of complex organic matter degradation.

the products of acidification, will be implemented; mainly, acid bacteria form acetate, carbon dioxide, and hydrogen. Acetic acid is formed from organic acids. The fourth phase, methanogenesis, involves methane-forming bacteria producing methane from acetic acid and hydrogen and carbon dioxide in two pathways: (1) the first group degrades acetate to CH_4 and CO_2 and (2) the second group uses hydrogen gas as an electron donor and CO_2 as an electron acceptor [44, 52, 55]. The early stages require acidic operating conditions while CH_4 is produced in later neutral conditions [55]. Chemical reactions through methanogenesis can be expressed as equations (1) and (2) under [56, 57]:

Autotrophic or hydrogenotrophic methanogenesis:

$$CO_2(g) + 4H_2(g) \longrightarrow CH_4(g) + 2H_2O(l) \qquad (1)$$

Acetoclastic methanogenesis:

$$CH_3COOH(aq) \longrightarrow CH_4(g) + CO_2(g) \qquad (2)$$

The bacteria involved in the range of phases of degradation have diverse necessities in terms of habitat (for instance, concerning pH value and temperature); a compromise must be found in the process technology.

3.2. Advantages and Disadvantages of Anaerobic Digestion Technology. The advantages of biogas technology (AD) are summarized: generation of renewable and low-priced energy supply (cooking, lighting, etc.), less demand for alternative fuels (protection of woodland, less soil erosion, and time saved for collecting firewood), on-site use of heat, nutrient protection, and inexpensive fertilizer (enhanced crop yields), BOD/COD and odor lessening, better hygiene (condensed pathogens and minimized disease transmission), enhanced living conditions, enhanced air quality, minimized GHG emissions, minimized nitrous oxide emissions, and long life span. The disadvantages include the need for expert design, skilled construction, and expert operation and maintenance, as well as expensive construction and less suitability for arid and cold climates and negative perceptions where there is low functionality of existing plants. Other disadvantages include the need for a reliable feed source and outlet for treated sludge, as well as the poor sanitation of the slush produced by mesophilic digestion [13, 15, 31, 38, 48, 58, 59].

3.3. Feedstock for Anaerobic Digestion in Sub-Saharan Africa. The biomass energy industry is still in its very early stages in sub-Saharan Africa (SSA) despite the region's abundance in biomass resources and a variety of biomass uses including solid fuels, liquid biofuels, electricity, and biogas [6]. The overall biogas production potential in SSA (excluding South Sudan and Sudan) from the feedstock available to communities, households, and at a commercial scale is projected to be 26.1 billion m^3, or 270 TWh of heat energy. Agriwaste accounts for the largest portion of this potential (36%) and offers the highest promise on a per capita basis as biogas feedstock [36]. SSA countries have vast technologically achievable resource potentials that are greater than the subcontinent's average energy consumption needs. A variety of biomass types can be utilized as feedstock for the production of biogas in AD systems, and the quantity and kind of feedstock to be used are the most crucial aspects to take into account while designing the system. The basis of feedstock for the digester is an important factor; the source must be reliable and sufficient.

Almost any type of biological feedstock can theoretically be used to generate biogas [31]; for an example, see Table 3. However, the choice of substrate will depend on the availability of the raw material, type of the digester, and its operating conditions [60]. As long as the biomass has cellulose, hemicellulose, proteins, lipids, and/or carbohydrates as major constituents, it can be used as feedstock to produce biogas. However, the feedstock's capacity to degrade physically and chemically is crucial [10, 28, 31].

For biogas production, the typical feedstocks used are animal waste (manure and slurries), human waste (excrement), agricultural crop and residues, organic wastes from dairy production, food and agro-industries, wastewater sludge, organic fraction of municipal solid wastes, organic wastes from households and from catering businesses, energy crops, and codigestion of multiple feedstock [22, 28]. The feedstock and the type of cosubstrate have an impact on the composition and yield of biogas, increasing the organic content and resulting in a larger gas yield [10]. The nature of the feedstock used determines the quality and quantity of the biogas yield (Figure 3). Biomass produces carbon and essential nutrients that facilitate the sustainable growth of the microbes in addition to the biogas yield. The optimum volume of biogas that can be produced from a unit of mass of a definite feedstock is called the biogas yield (BY) [61]. Substrates containing many sugars and fatty acids have a comparatively high biogas yield. Only the dry matter (DM), or the organic part of the dry matter (oDM), is determined for the BY. Hence, the yield can be calculated per kg of fresh matter (BYfm,i) or per kg of oDM. The BY is a hypothetical amount, and the practice also depends on other factors such as the pH and nutrient balance [60]. Additionally, according to the type of biomass material, the percentage of methane obtained from the resultant biogas also varies. So, the production of biogas depends on the mixture of components that are fed into the biodigester. As reported by Bond and Templeton [31], cattle dung is especially suitable as a substrate due to the presence of methanogenic bacteria in the stomachs of ruminants. To provide a family of five members, two cooked meals about 1500–2400 liter per day of biogas production are considered as sufficient [28, 31]. This shows that to provide enough biogas to cook for a family of five, a minimum of one pig, five cows, 130 chicken, or 35 people are required, as correlated with practical experiences in India [31]. The yield of biogas production potential and the weighted average percentage DM of selected potential feedstock in cubic meters per kg of various materials in dry matter (m^3 kg DM^{-1}) is summarized in Table 4 alongside the biogas yield and daily production per raw material.

The nature of the feedstock determines the quantity and quality of the biogas yield in addition to the variability of different parameters [56, 62]. In AD processes, a large number of organic materials can be exploited as feedstock. A comparative analysis of biogas yields from various potential feedstock is illustrated in Figure 3.

The food waste composition at postconsumer phase is shown in Table 5. The biogas yield and percentage of DM per good were also shown.

Table 3: Different feedstock from different sources [78, 101].

Feedstock sources/category	Different feedstock
Agriculture	(i) Animal manure
	(ii) Crop residues
	(iii) Algal biomass
	(iv) Energy crops
Industry	(i) Dairy residues
	(ii) Food/beverage processing
	(iii) Slaughterhouse/rendering plant
	(iv) Starch industry
	(v) Biochemical industry
	(vi) Sugar industry
	(vii) Pharmaceutical industry
	(viii) Cosmetic industry
	(ix) Pulp and paper
Communities	(i) MSW
	(ii) OFMSW
	(iii) Sewage sludge
	(iv) Food remains
	(v) Grass clippings/garden waste

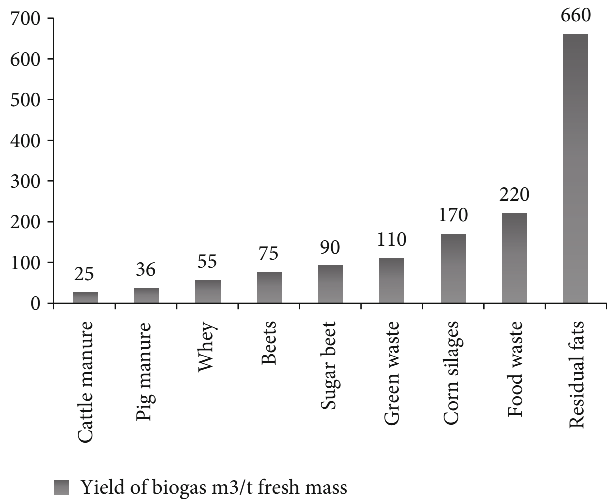

Figure 3: Biogas yield in cubic meter per ton fresh mass.

Achinas et al. [10] compare the production amount and energy potential for the different feedstock that can be utilized for biogas production (Table 6).

3.4. Anaerobic Co-digestion of Feedstock. Co-digestion is referred to as anaerobic treatment, digesting a homogenous combination of two or more different feedstock types simultaneously in order to stabilize the process and optimize biogas production (e.g., animal slurries and organic wastes from food industries) [22, 63, 64]. The utilization of codigestion practice regularly enhances the biogas yields from anaerobic conditions as a result of positive synergisms established in the digestion medium and the contribution of lost nutrients by the cosubstrates [45]. Many studies in recent years over AD have been focused on codigestion and are common to most biogas applications today, to enhance the organic content and accordingly attain a higher gas yield [10]. This technique is one of the most familiar strategies to overcome the

Table 4: Generation of biogas from selected feedstock [28, 31, 65, 101].

Feedstock	Daily production (kg head^{-1})	%DM	Biogas yield (m^3 kg DM^{-1})	Biogas yield (m^3 head^{-1} d^{-1})
Pig manure	2	17	0.25–0.5	0.128
Cow manure	8	16	0.2–0.3	0.32
Chicken manure	0.08	25	0.35–0.8	0.01
Human excreta	0.5	20	0.35–0.5	0.04
Food waste	—	34	0.55	—
1 : 1 mixture of cow manure and human excreta	—	18	0.407	—
1 : 1 mixture of food waste and human excreta	—	27	0.489	—
Alfafa	—	14-35	0.43-0.65	—
Rice straw	—	87	0.18	—
Rice straw	—	86	0.014-0.018	—
Bagasse	—		0.165 (m^3/kg organic DM)	—

Table 5: Composition and properties of food waste [12, 28].

Commodity group	% of total postconsumer waste	%DM	Biogas yield (m^3 kg DM^{-1})
Meat	10	17	1
Oil seeds and pulses	3	92	0.95
Roots and tubers	8	12	0.65
Cereals	28	88	0.65
Fruits and vegetables	48	13	0.4
Fish and seafood	2	—	—
Milk	1	8	

Table 6: Comparison of biogas yield and electricity produced from different potential substrates [10].

Type	Biogas yield (Nm^3 ton FM^{-1})	Electricity produced (kWh ton FM^{-1})
Cattle dung	55–68	122.5
Chicken litter/dung	126	257.3
Fat	826–1200	1687.4
Food waste	110	224.6
Fruit wastes	74	151.6
Horse manure	56	114.3
Maize silage	200/220	409.6
Municipal solid waste	101.5	207.2
Pig slurry	11–25	23.5
Sewage sludge	47	96.0

FM = fresh matter. Heating value 21 MJ m^{-3}, 55% methane content, and 3.6 MJ (kW·h) $^{-1}$.

complexities and limitations of a particular feedstock material. In several anaerobic co-digestion studies, cattle manure was taken as the major feedstock to encourage the digestion process successfully and efficiently. Further resources such as byproducts from food processing industries, activated sludge, municipal and industrial organic waste from households and industries, agricultural residues, and waste, were used [54]. Co-digestion by a carbohydrate-rich source and feedstock with less nitrogen can overcome the drawback of animal dung by extensively improving biogas generation [48, 65, 66]. Fortunately, codigestion can utilize the nutrients in various wastes and balance the bacterial community to optimize digestion performance [67]. In the AD process, the advantages of co-digestion are summarized as follows: selectively improving the biological and nutrient environment in the digester, better digestibility, enhancement of the process stability, an increase of nutrients; enhanced biogas production and the methane yield, achievement of better handling of the waste, a mixture of various waste streams that have varied characteristics in one treatment facility, and is key to improving waste management and sanitation [63, 64]. Thus, to improve either the quality of biogas or to maximize gas yield, further research is needed to identify suitable cofeedstock.

3.5. Factors Affecting Anaerobic Digestion Process. Anaerobic digestion (AD) is an important process for biogas production, and it is evident that AD processes are sensitive to environmental conditions for anaerobic microorganisms and are easily influenced by several different parameters for optimum performance. Efficient production of biogas through AD depends on several factors investigated in several studies. These studies are generally related to digesters, operating conditions, and the removal and biogas production efficiency. The main factors affecting the biodegradation process to improve the efficiency of AD in the production of biogas have been identified as temperature, pH, nutrient supply (C/N ratio), exclusion of oxygen, presence of a volatile substance, substrate composition, time retention, organic loading rate, and mixing ratios, and other parameters on AD have been studied intensively [22, 52, 53, 68–72]. A symbiotic relationship is essential between the hydrogen-producing acetogenic microorganisms and the hydrogen-consuming methanogens. Some of these key parameters are described below.

3.5.1. Temperature. Generally, the rate of reaction increases with rising temperatures. Biological processes, however, have optimum temperatures because organic structures (e.g., proteins) are liable to become unstable as temperatures rise and can lose their functionality. AD is strongly affected by temperature in biogas production [73]. The AD process can take place at three temperature ranges to operate microorganisms in anaerobic digesters: psychrophilic (<25°C), mesophilic (25°C–45°C), and thermophilic (45°C–70°C) [22]. Most of the acid-forming microorganisms grow under an optimum temperature of mesophilic conditions, and the increasing temperature has a positive effect on the metabolic rate of the microorganisms for methanogens, which can lead to a time reduction required for the digestion process and the process runs faster, which decreases the rate of biogas generation [60, 70, 73].

3.5.2. pH Value. Biological processes are heavily dependent on the pH value. pH monitoring and control in the AD process are important because the pH in the digester affects the performance and efficiency of the AD process. Through the AD process, alkalinity is a better indicator of process performance and directly shows the system's buffering capacity. This can be controlled by adjusting the pH value. So, pH adjustment could provide a way to improve the self-buffering capacity of AD systems to meet the requirements of microbial populations [67, 71]. In support of the AD process, the pH has a significant effect on the digestion process [73]. It influences the activities of specific acidogenic microbial populations and methanogenic bacteria and as a result affects the process constancy [71]. A neutral pH is the most favorable for AD biogas production since most of the methanogens grow at the optimum pH range of 6.8–7.2. However, the process can tolerate a range of 6.5 up to 8.0 [70, 73].

3.5.3. Carbon/Nitrogen Ratio. The other crucial parameter that represents the relationship between the amount of nitrogen and carbon in a substrate during the AD process is the C/N ratio. Carbon and nitrogen are two important sources of food for anaerobic bacteria, where carbon is required for energy and both carbon and nitrogen are important for building the new cell structure [74]. If the C/N ratio would be in an optimal range of 25-30 : 1, a digestion of feedstock will proceed more rapidly which produces optimal gas production [55, 75]. This led to the conclusion that the bacterial community uses up carbon 25–30 times faster than nitrogen. If the ratio is not sufficient, the nitrogen would get exhausted while there would be some carbon missing, which will cause bacteria to die. To meet their protein requirements, methanogenic bacteria utilize nitrogen. On the other hand, a surplus of nitrogen would lead to ammonia formation which will inhibit the digestion process. A low ratio means that the material is protein-rich. AD of such material results in an increased content of free ammonia that causes high pH leading to methanogenic inhibition [55, 66]. Higher C/N ratio causes fast reduction of nitrogen causing lower gas production. An optimum amount of carbon content has positive effect on avoiding excessive ammonia inhibition [55, 60, 75].

3.5.4. Mixing. Mixing is also an essential parameter in the AD process to ensure the efficient transfer of organic material and nutrients to the active microbial biomass and speed up the process by exposing substrate material to bacteria and by homogeneous temperature distribution and buffering alkalinity for effective high-rate biogas production. Mixing of the digester content is conducted in numerous ways, continuous or intermittent at different frequencies. In comparing continuously vs. intermittently mixed high-loaded processes, stable conditions are more often obtained with the intermittent systems. Overmixing might stress microbes and possibly harm the syntrophic interactions that are crucial to AD, whereas insufficient mixing causes foaming. Either recycling of the produced biogas or mechanical techniques can be used for mixing. Methane-forming microorganisms grow slowly, and also, the parameters' mixing depends on reactor types and design and physical and biochemical parameters of substrate and is also determined according to local conditions [54]. However, the efficiency of the mixing system design in relation to colonization, the presence of dead zones, changes in viscosity/rheology, etc., seems unclear, and this area thus calls for further attention.

3.5.5. Hydraulic Detention Time (HRT). One of the other parameters affecting AD process is hydraulic detention time, which is different and broad depending on the type of processes. Retention time (hydraulic detention time) is the average time spent by the input slurry inside the digester before it comes out [45, 54, 56]. Longer retention times require a large volume of the digester and thus more capital, whereas shorter retention times are likely to face the risk of bacterial population washout. Between retention time and the digester temperature, there is a linear relationship up to 35°C, the higher the temperature, the lower the retention time, and the reverse is true [56]. Increasing the organic loading rate (OLR) in AD means decreasing hydraulic retention time [74]. Hydraulic detention time also depends on the nature of processes and type of reactor [54].

3.5.6. Organic Loading Rate. The organic loading rate (OLR) is a vital parameter as it shows the quantity of volatile solids to be fed into the digester daily or simply refers to the quantity of feed processed per unit volume of reactor per day [75]. OLR is also defined as the biological conversion capacity of the AD system or the mass of organic matter over digester volume over time. The organic loading rate is also highly affecting gas production. The change in OLR induced changes in the microbial community structure, abundance, and dynamics that decreased in biogas, which were linked to a decrease in both bacterial and archaeal biomass as analysis of the microbial communities indicated [7]. For obtaining the maximum biogas yield, long retention time would require inside the digester by complete digestion of the substrate and a correspondingly large size of digester [45]. The portion of the organic material solids that can be digested corresponds to volatile solids, whereas the rest of the solids are fixed. The "fixed" solids and a portion of the volatile solids are non-biodegradable. The definite loading rate depends on the types of feedstock fed into the digester because the kinds of feedstock determine the level of biochemical activity that will occur in the digester.

3.5.7. Feedstock Composition and Nutrients. The growth of microorganisms affects the AD process. Hence, to obtain efficient biogas production from a given substrate, there is a need to supply nutrients in adequate amounts and at the right proportions to sustain the optimal growth of the bacteria and archaeal communities. Many organic materials can be exploited as feedstock in AD processes, and in order to grow, bacteria require an adequate supply of organic substances as a source of carbon and nutrients (nitrogen, sulphur, phosphorus, potassium, calcium, magnesium, etc.) in addition to carbon, oxygen, and hydrogen. Agricultural residues and wastes usually contain adequate amounts of these elements. The feedstock should be slowly digested; otherwise, easily degradable substrates may cause a sudden increase in acid content [56, 60].

3.5.8. Concentration of Feedstock. In addition to the quantity of feedstock, it is also necessary to know the concentration and composition of the substrate in order to obtain a mass balance. Sum parameters such as the total solid (TS) content, dry matter (DM) content, and volatile solid (VS) content are used to determine the concentration. The concentration of solids in the influent to the biodigester affects the rate of fermentation. The solid concentration is defined as the quantity of fermentable material of the feed in a unit volume of slurry. For liquid substrates, it is also possible to use the chemical oxygen demand (COD) and total organic carbon (TOC). Only the first two parameters mentioned are relevant in practice. Within the substrate, the mobility of the methanogens is slowly damaged by increasing solid content. The solid concentration (6-9%) in the digester is best suited ordinarily [56].

3.5.9. Volatile Fatty Acid. Volatile fatty acids (VFAs) are one of the control parameters in AD as it indicate the activity of the methanogenic consortia [74]. In the AD process, the VFA profile and other fermentation products are basic in structuring both the bacterial and methanogenic communities involved in the process and process yields. In structuring the methanogenic community of anaerobic digesters, past studies have indicated that the concentrations of VFAs play an important role [7]. VFA also has been reported that the accumulation and production of VFAs could show inhibitory and harmful effects on AD process which could lead to slow production of biogas [75]. More particularly, the concentration profile of individual VFAs and especially the ratio between them can provide essential information for process monitoring and can serve as early indicators for potential imbalances. Regardless of the vast amount of research on the effect of VFA composition on methanogenic community dynamics, understanding of bacterial community dynamics is still limited and often contradictory [7].

4. Agricultural Biogas Digesters

Agriculture includes the most important portion of the nationwide financial system in most developing nations. Nowadays, small-scale biogas technologies in many developing nations have been developed as a means of renewable energy use, enhancing agricultural productivity and waste management. The agricultural biogas digesters are assumed to be those digesters that are processing feedstock from agricultural sources. SSA with its warm climates, is well-suited for small-scale biogas digester technology. The model and skill of biogas digesters vary from nation to nation depending on energy accessibility and affordability, environmental situations, and nationwide structures. According to their comparative size, purpose, and site, agricultural anaerobic digestion digesters can be categorized as family-scale biogas digesters, farm-scale biogas digesters, and centralized/joint codigestion digesters [22].

Family-scale biogas digesters are digesters that utilize feedstock derived from household and small farming activities for household cooking and lighting activities. Relatively, this technology is easy and widely used in developing countries such as Nepal, China, and India. Such digesters can be assembled with local resources and are inexpensive, healthy, and easy to manage and maintain. In SSA, a slow rate of biogas technology distribution is observed among households. However, women in rural households alter their behavior when biogas is promoted and firewood consumption is reduced. Particularly, with less time for firewood collection and cooking activities, women in households have more free time for useful activities to increase the household's income-generating sources [76].

Farm-scale biogas digesters are the digesters connected to only one farm, processing the feedstock formed on that farm. Several farm-scale digesters codigest small quantities of methane-rich feedstock, intending to enhance the biogas yield. It is also practical that a farm-scale biogas digester obtains and digests animal manure, food processing wastes, and agroresidues from nearby farms [22]. There are several kinds and idea of farm-scale biogas digesters around the globe. In Europe, countries like Germany, Austria, and Denmark are amongst the pioneers of farm-scale biogas production [22]. The literature described that the implementation of the biogas technology considerably reduced firewood dependence on smallholder farmers in SSA. The attitudes of farmers towards biogas technology were also important factors [14]. Currently, on-farm AD has the potential to create energy security for the crowded farm, change crop waste into valuable resources, make superior quality fertilizer, vary farm revenue, enhance rural investment and employment opportunities, and decrease odors, thus assisting good neighbour and community relations. Farm-scale biogas digesters have a range of sizes, models, and technologies. A few are extremely small and technologically easy, whereas others are relatively large and not easy [22]. The focus on the model of small-scale biogas digester-based farming plots in SSA has not yet been considered in previous work. For small-scale farmers in Asia and Africa, continuous, mesophilic (30–38°C), plug-flow, and wet processes—such as flexible balloon digesters, fixed dome digesters, and floating drum digesters—are the most preferred designs [77].

Centralized co-digestion digester is an idea based on processing animal wastes, collected from various farms, in a biogas digester centrally placed in the feedstock collection area [22]. Such biogas digesters can form a central part of a holistic farming structure, allowing the effectiveness of several features of the system to be maximized by offering energy for family use and generating organic fertilizer to improve crop productivity. There is important progress across various SSA countries to enhance the realization of zero-grazing systems [77].

5. Main Uses and Potential of Small-Scale Biogas Systems

5.1. Small-Scale Biogas Technology for Poverty Reduction in SSA. As a result of their frequent importation, fossil fuel-based energy sources have a negative impact on the macroeconomic balance sheets of nations, as opposed to biomass, which might produce value-added products, support economic growth, and reduce poverty. In order to fight poverty and enhance community health, it is essential to give developing countries access to dependable and clean energy. With such a plan, they can boost production and encourage economic growth. If communities do not have the capacity to light their homes after sunset, actions such as reading, household everyday jobs, and even small business activities must stop when sundown. Renewable energy resources are abundant, diverse, and underutilized in SSA, but they have not yet been used to improve the standard of living for the population as expected. The bulk of SSA countries employ a significant number of people in the biomass energy sector, who frequently provide money to numerous communities. The biomass energy sector contributes significantly to the national economy and can easily exceed other economic sectors in terms of offering acceptable employment opportunities for the less fortunate sections of society. The majority of SSA countries might see a significant gain in revenue as a result of increasing the biomass energy sector, which will promote sustainable economic and green growth.

It is possible to explain small-scale biogas digester benefits using poverty indicators [78]. The productivity and income indicators for poverty increase if families spend less time gathering biomass and more time earning valuable income. For the people and farmers involved, the production and use of biogas via AD improve the environment and socioeconomics. The generation of biogas enhances societal and economic conditions and increases living standards. Small-scale biogas digesters should produce at least 0.8 to 1 m^3 of biogas per day for a family in order to be useful. The family needs access to 20 to 30 kg of fresh feedstock every day to produce this much biogas. To achieve this, SSA farmers would need at least three or four domestic cattle that are night-stabled. Most households, particularly those in SSA (mainly East Africa), meet this requirement [78].

Small-scale biogas digesters could improve the lives of the poor, offer a substitute for the current nonsustainable biomass sources, and have a good impact on the society, environment, and economy in developing countries like SSA. However, an energy or economic strategy has not yet been effectively applied in Africa [78, 79]. Further investigation is needed to ascertain the potential benefits and challenges connected with the installation of small-scale biogas digesters in SSA in order to reduce poverty and increase opportunities for job creation.

5.2. Small-Scale Biogas Technology for Household Energy in SSA. The improvement of living standards, development, and economic growth are all dependent on having access to affordable, dependable, and sustainable energy. Energy distribution to isolated rural areas and underdeveloped communities is simple and effective with small-scale residential digester technologies. The alternative rural energy initiative in SSA must include biogas technology [78, 79]. Biogas, a renewable energy source, is primarily produced from a variety of organic wastes and biodegradable materials. It is also a promising clean energy source with the potential for a range of end uses, such as residential cooking, heating, and lighting, as well as industrial purposes including combined heat and power (CHP) generation, transportation fuel, or upgrading to natural gas quality for diverse uses [48, 65]. However, in rural areas of poor countries with household-scale digesters, the primary uses of biogas are limited to cooking and lighting [65]. Compared to fossil fuels, AD technology greatly minimizes GHG emissions by using nearby available sources. Additionally, using digestate as fertilizer has enormous value in agriculture and can significantly replace conventional mineral fertilizers [48]. Additionally, the SSA has committed to the development of renewable energy technology as important means of addressing global warming and reducing emissions [6]. By improving the energy balance of the future, biogas from AD in developing countries will not only help to reduce the importation of fossil fuels but will also significantly contribute to the preservation of the environment, the reduction of indoor air pollution, and the reduction of greenhouse gas emissions. Consistent, sustainable, and affordable energy services with the least amount of adverse environmental effects for a sustained period are not only important for growth but also key for SSA countries in which the majority are struggling to satisfy the current energy needs, which is one way to end poverty, support health and educational services, and improve socioeconomic growth.

5.3. Potential of Biogas Digestate Processing Technology for Nutrient Recovery. Digestate, which is the effluent or processed substrate that is taken out of the AD digester after biogas has been recovered, is another product that is produced via AD in addition to biogas. The digestive tract contains a lot of macronutrients and micronutrients. If the digestate is utilized as fertilizer for crops or in the growth of plants, the nutrients (nitrogen and other mineral components like phosphorus, potassium, and calcium) present in the feedstock will be recycled after the digestive process [80]. This increases the physical, chemical, and biological health of the soil while promoting agricultural productivity [47, 65, 81, 82], and the sustainability of the biogas production process gets better [82, 83]. In the process of AD, the feedstock's carbon content is transformed into methane and CO_2, while the nitrogen mineralized and phosphorus content are left unaltered [53]. While simultaneously minimizing the expense of mineral fertilizer and preventing the possibility of digestate dumping, using biogas digestate as organic fertilizers aids in maintaining or improving soil quality [82, 84].

An overview of practical digestate processing technologies is illustrated in Figure 4. The amount of impurities and pollutants that are present in the digestate depends significantly on how much of their chemical, biological, or physical nature is present in the original feedstock for AD. To ensure the secure recycling of digestate as fertilizer, quality monitoring of all feedstock kinds is essential [22]. Based on their dry matter (DM) contents, two different forms of digestate are widely recognized. AD digestate is available in liquid and solid forms and is nutrient-rich and contains undigested and suspended substances [85]. After the AD process, the materials that have been digested are divided into two fractions: solid and liquid. While the liquid portion is sprayed onto farmland, the solid components are composted. The solid digestate has a higher DM content (>15% DM) than the liquid digestate, which has a lower DM content (<15% DM) overall [47]. Using agricultural biogas digesters results in significant postdigestion matter production. Although occasionally the solids are greatly reduced, its volume is roughly comparable to the whole mass of feedstock used in the digestion process in a biogas digester. If a portion of the liquid is inverted as process water to the fermentation reactor in some biogas facilities, the digestate mass may be smaller [2]. Similar to compost, solid digestate can be utilized or composted alongside other organic wastes. Compared to liquid parts, it can be transported more cheaply over long distances [47]. As shown in Table 7. The type, composition, and management of the feedstock, in addition to the operating parameters and effectiveness of the AD process, have a considerable impact on the physical and chemical properties of digestate [25, 85].

From an environmental and financial standpoint, using AD digestate, a mixture of partially decomposed organic waste, anaerobic biomass, and inorganic matter, as organic fertilizer or soil conditioner, appears to be the best recycling option [86]. In comparison to raw animal manure and slurries, digestate has higher fertilizer efficiency because it is more homogeneous; contains more readily available nutrients; has lower total solids and total organic carbon contents, a lower carbon-to-nitrogen ratio, and a higher pH value; and contains more ammonium ($NH4^+$) with less odor. In accordance with optimal agricultural practices, applying digestate as fertilizer will significantly increase N-efficiency and lower nitrogen losses through leaching and evaporation [22]. Many published works have explained how biogas digestate has superior fertilization potential than mineral fertilizer [84].

Utilizing biogas digestate as organic/biofertilizer demonstrates a competent method of nutrient recovery in farming and reduces the external input of inorganic fertilizer, both of which are important factors in the efficiency and environmental performance of biomass production schemes. However, a number of potential parameters (including the distribution and content of the digestate, the manner of field application, and the timing) must be taken into account [84]. There is no integrated approach described in the published literature for digestate processing for nutrient enrichment, but the nutrients that are still present in digestate can be extracted and concentrated through the use of a variety of technologies and processes to improve nutrient management in agriculture and in waste treatment systems. Therefore, combining the use of organic and inorganic fertilizers is the best way to achieve a number of goals, including high yields, low farming costs, and less harmful environmental effects. Farmers may be more willing to use organic fertilizers because of the combinations' improved performance and lower costs for mineral fertilizer [84].

However, it is well known in SSA that some biogas users do not profit fully from the potential of biogas technology because of inadequate expertise (lack of knowledge and awareness), particularly when it comes to the exploitation of digestate, which is poorly understood. In contrast to non-biogas customers, the majority of biogas users in developing countries directly release the slurry to the environment, according to [53]. This was further demonstrated by the fact that some urban biogas users discharged the slurry into a neighbouring river or sewer network. Even worse than burning dung in traditional stoves is direct discharge into the environment. A substitute for recycling the nutrients is to turn the slurry into compost along with other organic wastes. Without proper slurry control, installing biogas would be a waste of resources. In both industrialized and some emerging countries, several optimization strategies related to digestate processing and treatment technologies have been tried. However, it appears that the majority of SSA countries have conducted only a limited quantity of thorough studies on biogas technology, notably digestate processing technology, in international peer-reviewed academic and scientific journals. Future thorough research on digestate composition and processing, treatment, application technique and rate, and its impact on various cropping systems is therefore required, with a focus on the soil and climate characteristics of SSA, in order to better understand its significance and offer a means of reducing poverty, increasing agricultural output, reducing the need for mineral fertilizers, and recycling nutrients.

6. Factors Hindering Household Biogas Digester Use and Implementation in SSA

One of the renewable energy sources that have the potential to change how communities, particularly those in developing countries, think about providing clean, sustainable energy to their rapidly expanding populations is biogas technology. It was not expected to have much of an impact, but it does not seem like most of these developing countries are adopting it or using it more frequently.

In SSA, one of the only methods to ensure food security is to increase smallholder productivity (agricultural output and household income). The majority of biomass resources come from forestry and agriculture. Consequently, the development of the biomass energy sector will be advantageous for rural areas [6]. The modern condition of household digesters in developing nations varies from one to another. By now, small-scale biogas digesters are enhancing

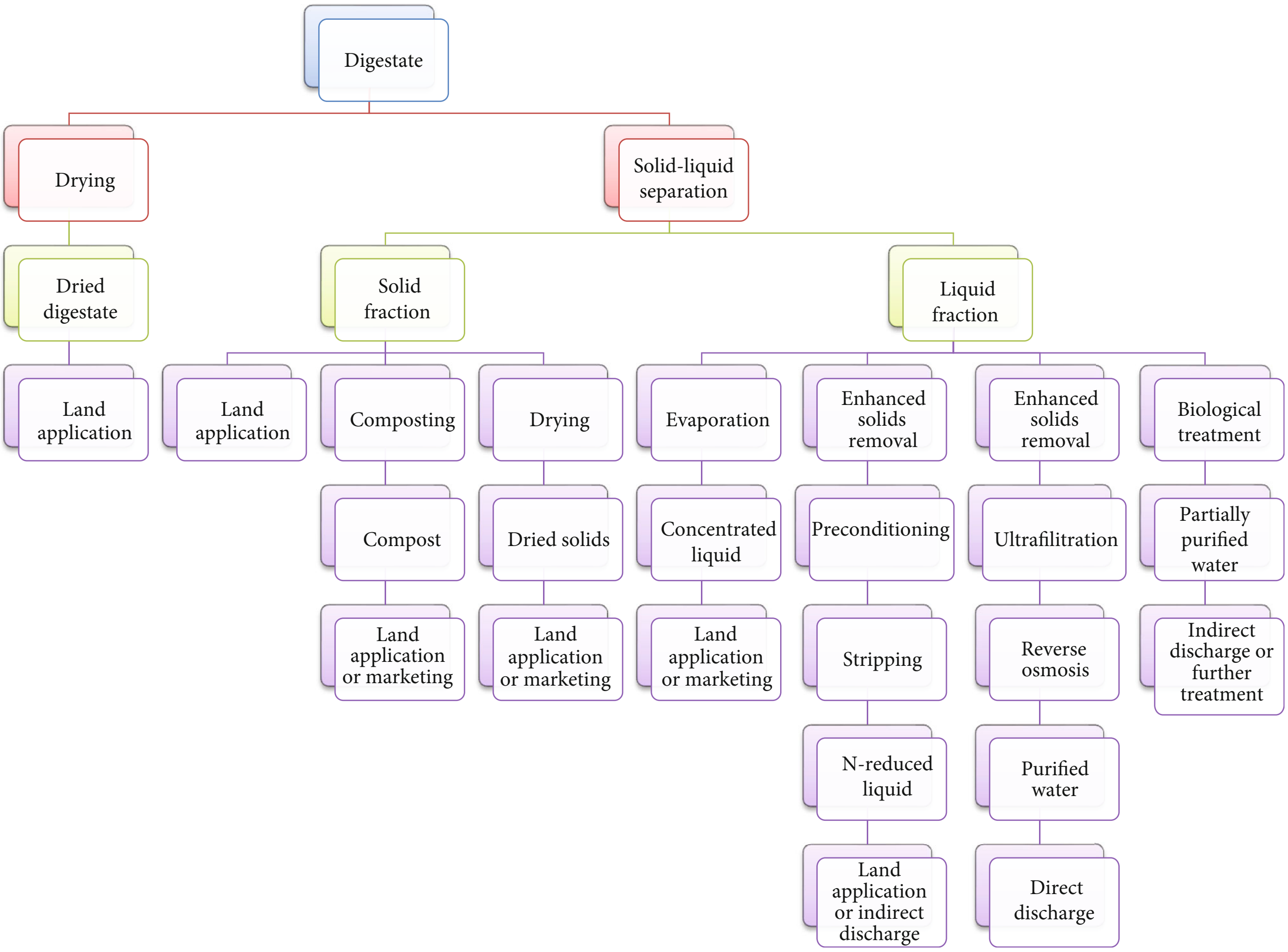

Figure 4: Overview of digestate processing viable options [80].

Table 7: Feedstock and process parameters affecting digestate composition [80].

Feedstock parameter	Digestate composition impact	Process conditions	Digestate composition impact
Organic wastes	(i) Low organic content concentration in TS (ii) Low content of total solids	High amount of fresh water	(i) High production of digestate (ii) Low levels of salt and ammonia (iii) Low TS content
Large amount of abattoir waste	(i) High concentration of nitrogen (ii) High % of NH_3 in total nitrogen	Recirculating liquid in large quantities (process water made from the liquid portion of digestate)	(i) Low production of digestate (ii) Excessive salt/ammonia concentrations (iii) A higher content of TS
High quantity of manure	(i) Low content of TS high nitrogen concentration	Short hydraulic retention time	(i) High quantity of volatile fatty acids (ii) Organic content in TS (iii) Low NH_3 content in total nitrogen
Energy crops	(ii) High content of TS (iii) High % of organics in TS (VS/TS ratio)		

the livelihood of poor people in various parts of developing nations by simultaneously offering biogas and digestate that can be utilized as fertilizer. In rural areas of SSA, this technology can replace traditional fuels (for example, firewood and charcoal) and compost or mineral fertilizers, which could be expensive for societies. However, in rural developing and underdeveloped societies, challenges related to high prices and skills in building, installation, and maintenance delay its dissemination [65, 87]. As was indicated before, several small-scale biogas digesters have been built [88] and are currently operating in several African nations using a variety of feedstock. However, when it comes to biogas and anaerobic technology, South Africa is the only SSA country with advanced anaerobic digestion [23]. Although the adoption of biogas digesters is less widespread than in other parts of the world and the sector is still in its early stages, biogas has the potential to significantly contribute to SSA's efforts to reduce poverty. As a result, residential biogas digesters are still used and distributed in both industrialized and developing countries. Different degrees of biogas generation between developed and developing countries are emphasized. Developed countries are largely concerned with large-scale biogas installations for CHP production, whereas underdeveloped countries are mostly concerned with small-scale biogas digesters that primarily supply heat for cooking. China has a significantly higher percentage of residential biogas digesters than the rest of the world [89].

Due to its integrated design and wide range of advantages (social, economic, environmental, health, etc.), small-scale biogas technologies have grown more appealing as nonrenewable fuel alternatives and as a means of promoting sustainable development. These advantages include increased opportunities for regional and rural development, the creation of domestic industry and employment opportunities, the diversification of energy (cooking and heating) supplies, the ability to burn more efficiently than fuels like wood and dung, the reduction of cooking time, the utilization of local resources, the minimization of local pollutants, the reduction of GHG emissions, the minimization of mineral fertilizer, the reduction of firewood use, and the improvement of air quality [25, 60]. Africa is claimed to have a large number of renewable energy resources, many of which are not being properly utilized, according to [89]. Therefore, by exploiting such underutilized resources, biogas digesters are promising solutions to provide the aforementioned benefits to households in rural SSA.

SSA countries face more sustainability and distribution problems than other developing countries, despite the significant potential benefits of residential biogas digesters. According to reports from earlier studies, a household's energy decision could be influenced by a number of factors. These factors can be divided into four categories: sociocultural (difficulties preventing people from utilizing the digesters), economic (capacity of the people), technical and training (capacity to manage the system), and institutional hurdles [40, 53, 89, 90].

From an economic point of view, costs and funding are the most frequently mentioned obstacles to the adoption of biogas technology in rural areas of developing countries like Africa, where the economy is mostly centered on survival and family farming [18, 25, 31, 91, 92]. A household's ability to pay for the new technology, the costs and advantages of installing biogas, and the effects on rural livelihoods must all be considered. The capital cost of a household digester may vary based on the materials, design, size, and location [25]. As a result, the greatest obstacle to the expanded use of biogas technology is the high costs associated with the installation, operation, and maintenance of biogas digesters, along with the poor purchasing power of many rural SSA households. Numerous farmers and residents of rural homes work as day laborers; as a result, they frequently lack the resources necessary to cover the high initial investment expenses in Africa. Additionally, the economic system in many emerging countries favors fossil fuels over renewable energy sources [65].

From a sociocultural point of view, challenges have prevented the development and widespread deployment of residential biogas technology in several SSA nations. Biogas is perceived as a polluting technology in many SSA nations, and societal stigma exists against its use. Because of the opposition from the community to using animal or human waste, as well as if it is not socially or culturally acceptable, it is of little use. Bansal et al. [32] indicated that in SSA, the use of home wastewater is necessary for the achievement of the biogas digester, since it is not done without it due to the cultural stigma attached to it. Therefore, the sociocultural hurdles can be overcome by intense educational and campaign initiatives that must be enhanced in order to improve understanding and consciousness of the advantages of biogas technology.

From a technical point of view, the provision of technical assistance and sufficient training for biogas users has not been made, and as a result, numerous systems fail or are ignored. Another barrier to the widespread adoption of biogas technology in the area is a lack of knowledge in the building and maintenance of biogas digesters [65]. In addition to other technical concerns [27], evaluated biogas appliances as one of the technical elements also impede biogas performance consumption. One of the technological barriers to biogas performance usage is biogas appliances.

There are numerous well-known varieties of biogas digesters in use today. The fixed dome, floating drum, and more recently, the plastic tube flexible balloon digesters are the three primary forms of residential biodigesters that have been available and used in rural parts of poor countries like SSA. The first two have been used often in Africa in developing countries, primarily using digesters on a household basis. This is due to the fact that the most typical residential digesters in developing countries are small in size ($2\text{–}10\,\mathrm{m}^3$) and primarily utilized to meet household-level energy demands for lighting and cooking. The amount of biogas generated by such a digester is insufficient for CHP or biomethane purification. The choice of the digester design is a crucial factor in determining the success of the implementation; if it is too expensive, impoverished farmers will not be able to take the risk of investing; nevertheless, if it cannot be easily maintained and is not healthy, farmers will not see the long-term benefits. Adopting one digester for household use is never simple. The design of household digesters varies depending on factors such as geographic location, feedstock availability, water supply, climatic conditions, local resources and skills, and labor availability [25, 60, 61].

The most common models implemented in SSA at the household scale have largely converged around fixed dome digester developed in China [17, 23, 25, 60]. Because of high upfront cost of the fixed dome design of digester, some argue that the cheaper flexible balloon models might provide a more inexpensive alternative and should be promoted as a substitute of fixed dome digesters [17]. Fixing of the flexible balloon digesters was a simple process. Every one installation took only a few days and is relatively inexpensive, and the method used for installation was simply learnt by users. Plastic bladder digesters do not give much insulation, so they are most appropriate in areas, where the weather is warm all year [20]. Problems with this model consist of possible damage of the flexible tube by sharp objects and UV sunlight, poor sanitation during manual use of manure, maintenance of gas pressure, and the elevated cost. Most of these problems are answered by giving better advice and repair kits with the digesters easily, but additional work is desired to decrease the price of flexible balloon digesters in SSA. Tumutegyereize et al. [93] also reported that there is a need for a shift from the common fixed dome type of digester to small and compact types which do not need large space in addition to substrate diversification and process optimization and control.

Last but not least, institutional obstacles such as weak policies, ambiguous institutional tasks, and shaky coordination at different levels of authority across institutions in several SSA nations present a problem for the introduction of biogas digester technology into the African market. Communities stop utilizing residential biogas digesters for a variety of reasons, including limited substrate supply, low gas production, and lack of expertise, according to [60].

Furthermore, Mengistu et al. [89] revealed that the success of biogas initiatives in Africa has been comparably poor. There are several causes listed for the issue. A few of the contributing factors are a lack of a focused energy policy, inadequate biogas installation design and construction, inappropriate user operation and maintenance, a lack of project monitoring and follow-up, and low user ownership accountability. Additionally, the technique has problems with SSA, including incomplete bioconversion, low methane outputs, unstable processes, and economic unviability. Clemens et al. [17], Mwirigi et al. [91], Bansal et al. [32], and Tolessa et al. [94, 95] recommended that implementation should depend on the program strategy.

An integrated program, such as technology standardization and quality control, integrated farming by using both biogas and bio-slurry at the same time, the mobilization of local and external funds, like from the clean development mechanism, to overcome initial construction costs, and the formation of user and disseminator associations for joint procurement and linkage to finance, can all improve household scale implementation. In order to provide household energy in SSA utilizing small-scale biogas digesters, it was therefore required to develop effective, safe, and affordable ways in addition to obtaining the most socioeconomic and environmental benefits from the digested slurries. Implementation of systematic evaluation tools that integrate technical, economic, social, and environmental performance will help farmers and supporting governments identify an appropriate solution to a specific context [8, 9, 96, 97].

7. Conclusion and Recommendations

The review highlighted the current status and prospects of small-scale biogas/AD system development in SSA. AD technology has the potential to impact all three pillars of sustainability, namely, economic, environmental, and social. AD has the economic potential to meet the demand for electricity and/or heat, produce organic fertilizer, and reduce waste disposal expenses. Regarding the environment, AD has the potential to reduce GHG emissions, lessen the amount of waste that ends up in landfills, provide clean energy, improve energy security, improve soil health, boost food production, and lessen the carbon footprint of agriculture. Investment, job creation, education and skill transfer, health benefit delivery, and raising living conditions in rural areas are examples of social components. Furthermore, this technology is one of several small-scale technologies that may provide the technical means for decentralized approaches to development in low- and middle-income countries.

The economic potential of AD as a sustainable agricultural practice includes the potential to supply energy/heat demands, produce organic fertilizer, and save waste disposal costs. From the environmental aspects, the potential of AD includes climate change mitigation (reduction in GHG emissions), reducing landfill usage, providing clean energy, increasing energy security, soil health, increased food production, and a lower agricultural carbon footprint. Social aspects include investment, job creation, skill transfer, and education opportunities that deliver health benefits and improve living standards in rural areas. In addition, this technology represents one of a number of small-scale technologies that could offer the technical possibility of decentralized approaches to development in LMICs. However, the technology has challenges in rural SSA countries due to incomplete bioconversion, low CH_4 yields, unstable processes, and nonviability from an economic standpoint. For these reasons, the majority of small-scale AD plants that have been installed in Africa have encountered multiple obstacles in their uptake and distribution, with a significant number of the plants being either not used at all or just used insufficiently. This review included several operating parameters that affect feedstock for AD and co-digestion technology, which in turn affects the AD process. It is revealed that maintaining the proper settings of numerous operating parameters that support the optimal growth rate of anaerobic bacteria is necessary for improving biogas generation. Furthermore, the review illustrated AD as the best technology available for producing clean, renewable energy, providing stabilized organic fertilizer rich in nutrients, and managing organic waste (which lowers GHG emissions and improves cleanliness). Subsequently, the article covered the many categories of anaerobic digesters and the kinds of small-scale anaerobic digesters utilized in developing African countries.

SSA is fortunate to have a wealth of biomass resources for AD technology. However, the development of technology for renewable energy and biofertilizer production has been comparatively slow and has encountered a number of challenges on the African continent. The difficulties include high upfront costs, a lack of a focused energy strategy and policy, a lack of experience in the design, operation, and installation of biogas digesters, a lack of coordination and capacity-building programs, a lack of project monitoring and follow-up, and low user ownership. The findings revealed that SSA has not yet completely benefited from all of the multiple benefits of small-scale household biodigesters. Prioritizing and identifying relevant and appropriate research and activity topics is necessary for this technology to have an impact. The findings also highlight that the successful implementation of this technology in SSA will also depend on the start of community-supported training programs, coordination and capacity-building initiatives, and the provision of low-cost, locally appropriate biogas digester design and construction that is accessible to all.

Even though the technology is old, there are still issues that prevent widespread use. The findings indicate that while there is a lot of literature on the design considerations for small-scale biodigesters, important design factors like digester safety, the quality of the biogas produced, and the safety of effluent discharge or use from small-scale biodigesters were not frequently covered in the literature, particularly for SSA. Moreover, there were no reports of standards or criteria being followed in the design of small-scale biogas digesters, which made it difficult to assess suggested designs and hampered the advancement of policies that support the technology.

Although the approach used in this study has yielded some interesting findings and conclusions, it is important to acknowledge its limitations. The selection of literatures for the review unavoidably excluded some studies that were not published in indexed journals, including blogs, social media, websites, and other online publications that would have provided useful information for the research. An investigation encompassing multiple databases has the potential to enhance the review process. Further research should take into account the development of guidelines for digester design that follow best practices. More research is required on the topics of safe effluent usage or disposal and acceptable grade biogas generation.

Acronyms

ABPP:	African Biogas Partnership Program
AD:	Anaerobic digestion
BOD:	Biological oxygen demand
BY:	Biogas yield
COD:	Chemical oxygen demand
C/N:	Carbon to nitrogen ratio
CHP:	Combined heat and power
DM:	Dry matter
FM:	Fresh matter
GHG:	Greenhouse gas
Hivos:	Humanist Institute for Development Cooperation
NDBP:	National Domestic Biogas Programs
OLR:	Organic loading rate
oDM:	Organic dry matter
SNV:	Netherlands Development Organization
SSA:	Sub-Saharan Africa
TOC:	Total organic carbon
TS:	Total solids
TWh:	Terawatt hours
UV:	Ultraviolet
VFAs:	Volatile fatty acids
VOC:	Volatile organic carbons
VS:	Volatile solids.

Data Availability

The research data supporting this review paper are from previously reported studies, which have been clearly cited.

Conflicts of Interest

The author declares that there are no conflicts of interest.

Authors' Contributions

AT conceived, designed, and reviewed literature; analysed and interpreted the data; contributed materials, analysis tools, or data; and wrote the paper.

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