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Review

Animal Manure as an Alternative Bioenergy Resource in Rural Sub-Saharan Africa: Present Insights, Challenges, and Prospects for Future Advancements

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Abstract: Energy availability is a pivotal driver in fostering sustainable socio-economic development. However, sub-Saharan Africa (SSA) grapples with paradoxes headlined by abundant energy resources but with the world's lowest access to clean energy index per capita. Faced with a lack of access to clean energy sources like electricity, rural areas in the majority of SSA countries almost exclusively depend on biomass-fuels, mostly fuelwood, leading to heightened respiratory health risks as well as environmental degradation and accelerated climate change. As an alternative, this review investigates the potential of animal manure as a sustainable energy resource for rural SSA households, emphasising its utilisation as a feedstock for biogas production using anaerobic digestor technology. Results show that despite the abundance of literature that reports on successes in lab-scale bioreactor optimisation, as well as successes in the initial rollout of biogas biodigester technology in SSA with the help of international collaborators, the actual uptake of biogas bioreactor technology by rural communities remains low, while installed bioreactors are experiencing high failure rates. Resultantly, rural SSA still lags significantly behind in the adoption of sustainable clean energy systems in comparison to rural communities in other regions. Among some of the hurdles identified as driving low technology assimilation are onerous policy requirements, low-level government involvement, high bioreactor-instalment costs, the lack of training and awareness, and water scarcity. Prospects for success lie in innovative technologies like the low-cost portable FlexiBiogas system and private–public partnerships, as well as flexible energy policy frameworks. Bridging the knowledge-implementation gap requires a holistic approach considering cultural, technological, and policy aspects.

Keywords: energy poverty; biogas; animal manure; sub-Saharan Africa; greenhouse gas emissions; climate change

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1. Introduction

Energy availability is the cog that drives sustainable socio-economic development [1,2]. However, the status of energy availability in sub-Saharan Africa has more than its fair share of paradoxes. Three facts that stand out are as follows: (i) the population of sub-Saharan Africa constitutes about 15% of the world's population [1,3]; (ii) the region is rich in energy resources and yet remains poor in energy supply, accounting for only 4.3% of the global energy demand [3]; and (iii) the region has the lowest level of access to electricity worldwide, with 75% of the global population without access to electricity residing in this region [1]. Presently, sub-Sharan African economies are overly dependent on fossil fuels such as oil, coal, and gas to power the various industries that are central to their economic growth [4]. Despite this over-reliance on fossil fuels, however, Africa and the sub-Saharan African region still contribute only approximately 2% of the aggregate global greenhouse gas emissions while the world's more developed economies like the USA, Australia, Germany, and China are responsible for the bulk of the emissions [5].

With greenhouse gas emissions being linked to worsening climate change, the evidence of which includes increasingly drier and hotter climatic conditions in some parts of the world while others experience unprecedented floods, wildfires, rising seas levels, among other changes, the discourse among developed countries is rapidly gravitating towards clean energy usage to mitigate the damaging effects of climate change [6,7]. However, less developed economies in the sub-Saharan Africa region will find it cheaper in the foreseeable future to consume readily available fossil energy sources despite their harmful effects to the environment [4]. At the household level, 76–80% of urban populations in the sub-Saharan African region have access to electricity for cooking and heating, while almost the same percentage (70%) of rural populations rely on unsustainable biomass sources, especially fuelwood [8,9], exposing them to respiratory health complications due to polluted indoor environments in addition to environmental degradation due to deforestation [10,11]. The persistently high demand for wood fuel in rural sub-Saharan African households is unsustainable as it directly threatens forests resources, thereby accelerating desertification, which inadvertently increases the region's carbon footprint and contributes to global warming [12]. In any case, The United Nations, through its non-binding Agenda 21, as well as the Kyoto Protocol, strongly advocate for the development of sustainable, climate-friendly renewable energy systems, particularly in the face of the imminent depletion of fossil fuels [13]. Hence, the need for appropriate investment in small-scale biogas technologies to achieve a self-sufficient paradigm shift from traditional to sustainable and climate-friendly modern bioenergy to deliver a range of benefits to rural households [14–16]. In this context, manure ought to be considered as a valuable resource, given its potential for anaerobic digestion, which stands out as a promising avenue for its sustainable management. The use of animal manure for energy generation, and in particular as feedstock for anaerobic digestor technology, has received extensive coverage in both the research and review literature globally as well as in the sub-Saharan Africa (SSA) context. The vast majority of this research, however, is focussed on anaerobic digestor-process improvement [17], in particular on feedstock choices for increased biogas output [18–20], bioreactor design and diagnosis of bioreactor failures [21], impacts of private–public partnerships on biogas technology development [22], and socio-economic barriers to technology adoption [23,24]. In so doing, lab-scale successes and achievements are often misconstrued for on-the-ground implementation success whereas, in practicality, there is a disconnect between research and implementation [25]. There is still a dearth of information with regard to the practicality of using animal manure as a clean energy source in rural SSA.

This review, therefore, plugs this gap by providing an in-depth analysis of animal manure as an alternative, sustainable energy source for energy-poverty-stricken rural sub-Saharan Africa (SSA). Emphasis is placed on current knowledge and the use of animal manure as an energy source, opportunities for growth, and the associated limitations, as well as on prospects for future advancements in rural settings. The focus on rural areas was informed by the fact that more people live in rural areas compared to urban areas in sub-Saharan African countries [8,26], in addition to the fact that, due to high poverty levels, energy poverty is felt more in rural areas than in urban areas. Consequently, there are high rates of deforestation in rural areas as residents harvest forest resources to meet their daily energy requirements.

2. Animal Manure as an Alternative Source of Energy in Rural SSA

Renewable energy resources continue to hog the spotlight in climate change debates due to their low carbon footprints [5]. Currently, these include solar, wind, hydroelectric, and biomass resources, which are soon to be joined by green hydrogen. Biomass, and animal manure specifically, is a centuries-old source of renewable energy, which can either be directly burned to produce heat energy (akin to coal or wood fuel) [7] or can be fed into an anaerobic biodigester to produce combustible gas called biogas [27]. However, the direct burning of dung pellets for heating and cooking has the disadvantage of producing smoke that pollutes indoor air and leads to chronic respiratory and eye infections, the same problem as occurs from burning fuelwood [28]. Besides the production of poisonous gases like carbon monoxide, sulphur dioxide, and nitrogen oxide, when directly burned as pellets, cow dung has a low heating value ranging from 10 to 17 MJ/kg, depending on its moisture content [7]. Anaerobic digestion, however, converts the biomass into energy-rich biogas, which is ultimately used as a clean renewable energy source for domestic cooking, heating, and lighting [13]. An added advantage is the production of bio-digestate, which is a nutrient-rich slurry that farmers can then apply to their fields as organic fertiliser to increase agricultural productivity. Furthermore, according to ref. [29], the application of digestate facilitates the settling of phosphorous and metals such as copper and zinc, consequently diminishing their discharge into surface waters preventing eutrophication or algal bloom. Within the anaerobic digester, the principal components undergoing alteration are carbon and nitrogen that result in an 85% reduction in biological-oxygen demand [30].

The development of anaerobic digester technology for biogas production presents a plausible avenue to ameliorate energy poverty, which is partly responsible for slow economic development in SSA countries [31]. What makes animal manure particularly ideal as a feedstock for biogas production is its high moisture and volatile-solids content [12]. In addition, animal manure also contains a diverse assemblage of microorganisms, some of which play significant roles during the anaerobic digestion process. For example, the microbial profile of cow dung consists of different bacterial species, including *Bacillus* spp., *Corynebacterium* spp., *Lactobacillus* spp., *Citrobacter koseri*, *Enterobacter aerogenes*, *Escherichia coli*, *Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Kluyvera* spp., *Morgarella morganii*, *Pasteurella* spp., *Providencia alcaligenes*, *Providencia stuartii*, and *Pseudomonas* spp., as well as protozoa and yeast (*Saccharomyces* and *Candida*), lignocellulolytic fungi, and archaea [32–34]. As a potential replacement for fossil fuels, biogas is produced when animal manure is subjected to anaerobic digestion by methanogenic bacteria, generating biogas whose composition varies from 45 to 70% for methane gas (biomethane) and 25–40% for carbon dioxide, as well as containing some trace gases, including hydrogen sulphide (<10 ppm), nitrogen (<3 ppm), and hydrogen (<1 ppm), depending on the animal source of the manure [12] This follows a four-stage process starting with hydrolysis, followed by acid-genesis and acetogenesis that are induced by a specific consortia of bacteria, with the final step of methanogenesis undertaken by a consortia of methanogenic archaea, as detailed in the extant literature [2,13,27,31,35], and as shown in Figure 1 below.

A study by [2] reports that in a supervised anaerobic digestion, cow dung and poultry litter can produce biogas yields of 0.034 and 0.03 m^3/kg, respectively, with methane concentrations of 60% and 62%, respectively. Biogas with such methane compositions is not only comparable to fossil fuel derived natural gas that is 75–98% methane [2,13] but is also classified as good-grade gas since biogas burns more effectively when its methane component is greater than 50% [31]. In terms of heating value, [36] report that the heating value of pure methane (natural gas) is 8900 kcal/m^3 whereas the heating value of unpurified biomass-based biogas is in the range of 4800 to 6700 kcal/m^3, with a cooking efficiency of approximately 55% on a small scale. Furthermore, research shows that the energy value of 1 m^3 of biogas is between 2000 and 4000 kcal, which can meet the cooking needs of a family of 4 to 5 people for 3 h, with about 3 m^3 of biogas needed to cater for the family's cooking needs per day [36]. Regarding anaerobic digester performances, ref. [2] notes that the cause of irregular and inconsistent biodigester performance is usually a lack of supervision, which often results in digester underfeeding, improper water mixing, and irregular feeding, which all reduce yields significantly. With adequate training and consistent use, however, people reliant on digesters for biogas production should be able to solve these problems.

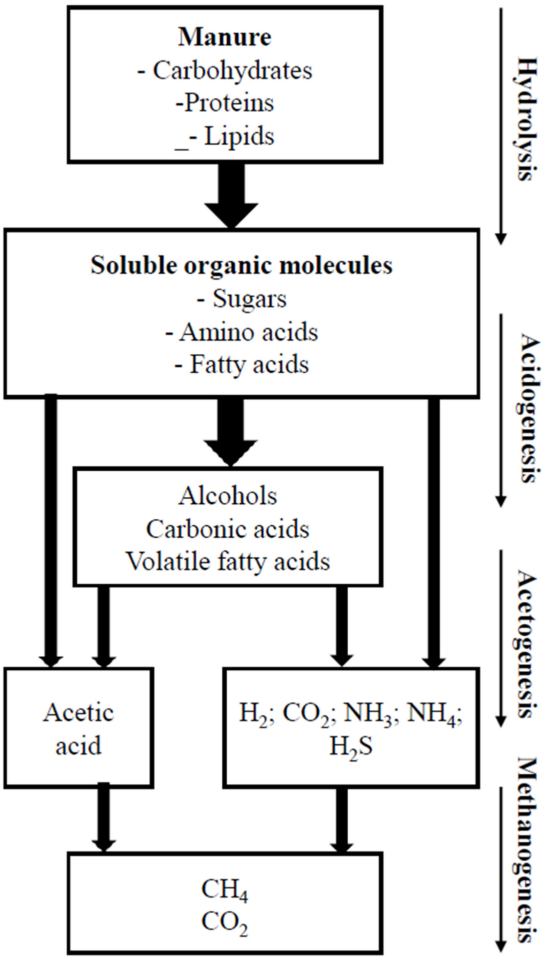

Figure 1. Stages in the anaerobic digestion process for the production of biogas from animal manure.

2.1. Present State of Knowledge and Use of Animal Manure for Energy in Rural SSA

The present understanding and use of manure for energy in rural SSA reveals a nuanced landscape shaped by historical practices, international collaborations, and regional variations [37,38]. The use of animal manure as feedstock for the generation of biogas using fixed-dome and floating-drum digesters has been practiced in sub-Saharan Africa since the 1950s [28], howbeit on a scale too small to tilt the scales towards economic development [37]. In Kenya, for example, biogas was introduced in 1948, with the first biodigester being built in that country in 1957 by the company Tunnel Engineering Ltd. [37,39]. Other early pacesetters are South Africa, where biogas digesters were set up in the 1950s, and Tanzania that began in 1975, while the most recent newcomer to the technology is South Sudan, where the first biogas digester was installed in 2001 [40]. To date, and through public–private partnerships, anaerobic digester technology for biogas production has been rolled out in different rural areas of Kenya, mostly using cow dung as the main feedstock [39]. An organisation called the Netherlands Development Organisation, founded in the Netherlands in 1965, provides technical assistance to the Africa Biogas Partnership Programme (ABPP) supporting national programs on domestic biogas in several sub-Saharan African countries, including Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso [9,39]. This has seen over 18,000 biodigesters being installed across Kenya since 2009 [39]. In addition to ABPP, another organisation, the International Fund for Agricultural Development (IFAD), which is funded by the UK Department for International Development, has been assessing the potential of renewable energy technologies like biogas in conjunction with a Keyan company, Biogas International Limited (BIL), since 2012 [28]. IFAD has also facilitated south–south cooperation between Kenyan engineers and the Indian Institute for Technology, providing a platform for scaling up the biogas technology in Kenya and beyond [28]. The African landscape is characterised by three different size types of biogas digesters which include the household digester plant whose gas production capacity is designed to meet all the cooking and 2–4 h of lighting needs of a family; the institutional/community digester plant that is typically shared by neighbours, and the large-scale plant that is designed to supply gas to closed communities [40]. Rural areas are typically serviced by either family plants or institutional plants, depending on population distribution. Historically, the fixed-dome bioreactor has been favoured over other designs like the floating-drum bioreactor due to its perceived durability and low maintenance costs [40].

In terms of biogas technology uptake, countries in southern Africa have been slow compared to countries in western, central, and eastern Africa, which embraced international collaborations to build public–private partnerships as support structures in setting up national domestic biogas programmes that have supported the increased uptake of the technology compared to countries in southern Africa. While statistics is scarce, ref. [41] show that, as of 2005, several southern African countries like South Africa, Swaziland, Zimbabwe, and Botswana had approximately 100 medium/small-scale digesters (100 m^3) each, Burundi (central Africa) had more than 279 digesters, and Tanzania and Kenya (eastern Africa) had more than 1000 and 500 digesters, respectively. While a lot might have changed since 2005, data in Table 1 show that it is the central and east African countries like Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin, and Burkina Faso that have increased the uptake of biogas technology, even going as far as increasing the number of trained technicians for both installation and maintenance of biodigesters, with solid plans for expansion [37]. Contrastingly, not much development has been realised in southern sub-Saharan Africa outside of South Africa, where significant progress is being made [42].

Table 1. Distribution of biogas digester facilities in some SSA countries.

Country	No. Installed	Capacity (m^3)	Operational (%)	Reference
Zambia	60	4–80		[23]
Zimbabwe	711	50–200	15	[43,44]
Ethiopia	15,738–18,534	Various	40	[24,45,46]
Cameroon	164 *	Various		[46]
Burkina Faso	10,310	Various		[46]
Botswana	15	Various		[46]
Kenya	13,000–18,560	Various	30	[24,46,47]
Senegal	875	Various		[46]
Tanzania	12,000	Various		[48]
Uganda	8000	Various		[47]
Nepal †	431,629	various	90	[49]

* Data relates only to domestic-level bioreactors. † Nepal is included for benchmarking purposes.

In terms of digester feedstock/substrate, while animal manure is the main type used in sub-Saharan Africa, ref. [41] points to a combination of food waste and human excreta, rice husks, and banana and plantain peels as well as groundnuts as among some of the unconventional substrate types used in pilot studies in Nigeria. The use of human excreta for biogas generation in rural communities is likely to be met with stiff resistance rooted in cultural beliefs and there may not be any food waste at all due to food insufficiency in these settings. However, while there is hope for a change in human perception and cultural beliefs, what is more concerning is that the available literature points to a mismatch between laboratory-scale manure-to-biogas research and actual biogas rollout in sub-Saharan Africa. The scholarly literature is concerned mostly with optimising anaerobic digestor conditions for optimal biogas output but offers little insight about the actual use of animal manure for energy generation. In the majority of cases where anaerobic digester technology has been rolled out, refs. [23,25] point to a high failure rate where biogas plants lie unused due to, among other factors; a lack of state investment in biogas research, difficulty in accessing biogas technology within some national contexts, a lack of supportive policy frameworks in some countries, low institutional capacity to implement national biogas programmes, prohibitive regulatory barriers, insufficient feedstock, the constant cost of maintenance, a lack of training for potential biogas owners, and climate unpredictability that leads to water shortages and ultimately anaerobic digestor failure.

Differences in biogas adoption rates between Asia (using Nepal as an example of a developing Asian country) and SSA are influenced by, among other things, the cheaper cost of building materials in Nepal (Asia) as compared to SSA, the higher numbers of livestock and hence available feedstock in Nepal compared to SSA, differences in the availability of loans for biogas infrastructure installation in Nepal compared to SSA countries outside of South Africa, and the relative maturity of biogas promotion schemes in Nepal, where it was first introduced in 1992 as the Biogas Support Program, compared to SSA where the first scheme was introduced in Rwanda in 2007 [24,49]. Intriguingly, there were already 11,919 installed biogas plants in Nepal by the year 1992 when the support scheme was introduced. Again, unlike in SSA where most national governments are struggling, at the policy level, to steer development of the biogas sector, Nepal has managed to institutionalise the biogas industry through a line agency called the Alternative Energy Promotion Centre (AEPC), which was set up under the Ministry of Science and Technology in 1996 to promote renewable energy projects in that country [49]. The AEPC was set up with a clear mandate to "form and organise policies on the distribution and implementation of RETs to boost rural people's living conditions through clean energy supply and protection of the local environment from deterioration" [49]. This made it easier for Nepal to receive international funding to support its biogas industry, resulting in an over 90% success rate compared to a 40% maximum success rate among SSA countries. Nepal lies in an earthquake prone area, and in 2015, 16,721 biogas plants were earthquake damaged. However, by the year 2018 the Nepalese government had already repaired 43.8% of the damaged plants [49]. Comparatively, Zimbabwe currently has 68 non-functional digesters, 26 abandoned digesters, 3 collapsed digesters, and 7 digesters that never have worked since being commissioned (Table 2). SSA governments therefore still have a lot to learn from successful examples like Nepal if they are to turn around the fortunes of the once hyped but underdeveloped biogas industry.

Table 2. Status survey of Zimbabwe's biodigester infrastructure from 1980 to 2012.

Year of Construction (Phases)	No. Collapsed	No. Functional	No. Non-Functional	No. Yet to Be Fed	No. Abandoned	No. Never Worked	No. under Construction
1980–1990	0	2	21	0	7	2	2
1991–2000	0	6	17	0	6	3	0
2001–2010	3	5	30	2	13	2	2
2011–2012	0	1	0	0	0	0	2
Total	3	14	68	2	26	7	6

Source: [44].

2.2. Opportunities and Challenges

Biogas has the potential to supply a more sustainable source of energy than solid biomass like wood fuels in rural households in sub-Saharan Africa [50]. The biggest opportunity for the development of biogas technology in rural sub-Sharan Africa is the vast availability of biomass, particularly animal manure [51]. This is because the main economic activity in rural sub-Saharan Africa is farming, with cattle and small stock rearing playing a significant role in sustaining those local economies [52]. Furthermore, farmers tend to house their livestock in kraals during the night, making it easier to accumulate significant amounts of manure in a short period of time [51]. For example, ref. [53] estimate that the livestock population in Ethiopia is about 150 million, with an estimated 42 million tonnes of dry-weight dung per year, 84% of which is produced by cattle alone. In another example, a study by ref. [54] in rural Vhembe District in the Limpopo Province of South Africa estimated the following animal populations: 1,050,685 cows with an estimated 12 kg of manure per animal per day, equivalent to an estimated 0.2 Nm^3 of methane per day; 373,037 pigs (5 kg/animal, 3.6 Nm^3 methane); 1,542,903 chickens (0.08 kg/animal, 0.35 Nm^3 methane); 253,139 sheep (6 kg/animal, 0.053 Nm^3 methane), and 1,147,987 goats with an estimated 6 kg manure output per animal and an estimated equivalent of 0.367 Nm^3 of methane per day. Assuming these numbers to be representative of approximate animal populations in all of South Africa's provinces, they represent huge renewable energy resources that have the capacity to confine South Africa's energy deficiency to history if utilised for biogas generation. Conversely, these statistics also show the amount of environmental damage that is currently ensuing because of the unmanaged animal manure, with statistics indicating that every 1 kg of cow dung can release about 60 L of gas emissions into the atmosphere, the largest component of which is methane gas [36]. However, adopting the biogas technology hinges upon various factors, including environmental, economic, technical, and social factors [55]. It is imperative to scrutinise seasonal and geographical variation in the composition of specific of manures [14]. These considerations will profoundly determine the technical and economic feasibility of accessing manure. The availability of manure is linked to the organisational structure of animal husbandry, displaying regional differences [14].

In addition to the ready availability of animal manure, farmers who rear mixed stock also get different kinds of manure that can be mixed for optimum biogas production. In a supervised anaerobic digestion experiment, ref. [34] reported that mixing cow and pig dung with water at a ratio of 3:2:5 resulted in a 10% increase in methane production. In yet another study, ref. [35] established that mono-digestion of either chicken or goat manure alone resulted in lower biomethane production compared to co-digestion of chicken and goat manure, attributing that to the balance of micro- and macronutrients that favour microbial metabolism and pH regulation in a co-digestion set-up. Meanwhile, use of a single type of feedstock may result in poor biogas yields if the feedstock used is either recalcitrant to digestion or has a low carbon to nitrogen (C:N) ratio [13]. Other advantages of resorting to biogas as an alternative source of energy include the fact that the production of biogas does not need external application of energy (besides the feedstock), and that it is a simple and low-cost technology that is easy to set up [13]. In view of the rugged terrain characteristics of many rural settings, low population density, as well as the often-irregular patterns of household distribution, the cheaper and technically viable option is to decentralise the energy distribution system by setting up small-scale anaerobic digesters household by household [38]. It is estimated that the cost opportunity for a unit of biogas energy over a digester's 15 to 20-year life span is bound to be lower than either a unit of solar energy or the cost of extending a conventional electric grid [56]. Furthermore, estimates report that, with a supply of around 25 kg of animal manure per day, biogas equivalent to 2 L of kerosine can be produced a day, which is enough to meet the energy cooking needs of a family of six [36]. Perhaps the standout advantages of converting animal manure into biogas are that (i) the biodigester facility can be located anywhere where sufficient biomass feedstock is available, making it particularly suitable for rural areas where farming is the main economic activity; (ii) power generation is not time-bound and can be generated when and where needed, as long as sufficient biomass feedstock is available; and (iii) the generation of gas or electricity or both in a rural setting promotes industrialisation of such communities [27]. Additionally, unlike solar energy, biogas can be easily stored without the need for batteries [9]. Also, although the primary recognized applications of digestate are as a soil supplement through land application and as a biofertiliser, within the realm of a bio-based economy the digestate can also be used for various other value-added products such as algae cultivation and biosorbent production [57]. These advancements underscore the need for a shift towards leveraging animal manure as a valuable resource not only for bioenergy production but also for promoting sustainable development as well as mitigating environmental impacts associated with waste disposal. Therefore, livestock manure management under a biorefinery approach seems a fitting solution for future sustainable development that meets the demands of a circular bioeconomy.

However, despite the enormous potential that biogas has of transforming the fortunes of citizens in rural SSA, the biggest hurdle to the adoption of this technology is that it is seen as too complicated and expensive [56]. The claim is not without merit, because the initial investment costs, especially the costs of either buying a prefabricated biodigester or the materials needed for constructing a biodigester, are usually too steep for poor rural households to foot in a single payment [37]. The traditional brick dome biodigesters (Figure 2), while reliable and durable, generally require expertise to construct, in addition to the high cost of the materials required [26].

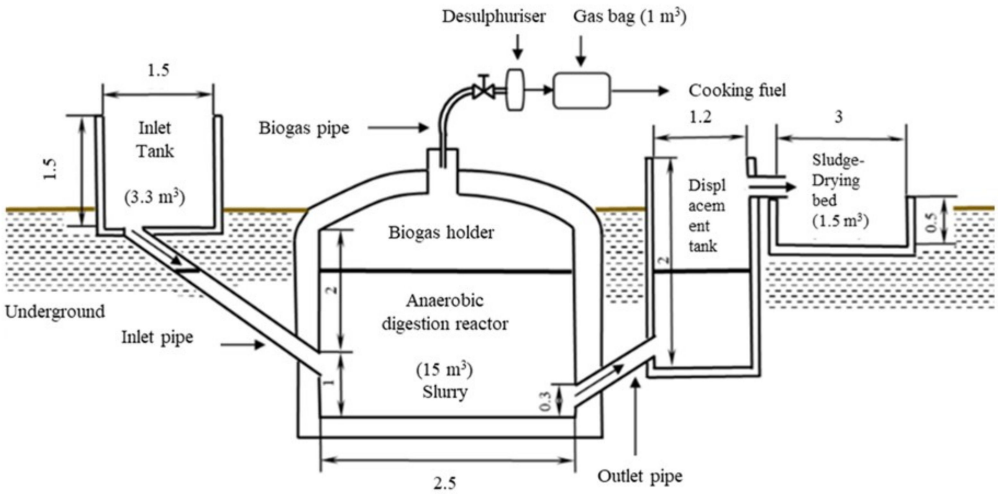

Figure 2. Schematic diagram of a fixed-dome biogas digester with dimensions measured in meters [58].

Biogas technology does, however, become cheaper in the medium to long-term when taking into consideration the health benefits, the lower time and/or cost spent on firewood collection/purchase, as well as the lower time spent on cooking. There is a need for an integrative strategy aimed at ensuring the full participation and technology buy-in of the target rural communities. Currently, the major limitation to the rollout of biogas technology in sub-Saharan Africa is that, while most national governments in the region mention the word 'biomass' in their renewable energy policy documents, most lack concise implementation timelines and methodologies and thus the rate of transformation of policy into reality on the ground remains low [59–62]. By contrast, in China, for example, renewable energy policies have been used to support the installation of household scale digesters in rural areas, which now account for 70% of China's installed biogas capacity [63]. The technology buy-in of rural communities should be coupled with information dissemination about the potential of animal manure in not only easing energy poverty but also eradicating the health risks associated with indoor house pollution emanating from the use of wood fuel, supporting conservation of forests, and supporting employment creation as well as a general advancement in the quality of life. Admittedly, this will require decentralisation and devolution of powers from national-level to community-level leadership structures. Also, apart from local utilisation, biogas cannot be easily liquified and bottled for sale or export unless it is further enriched to increase its C:N ratio, which can present huge technical challenges. Another potentially limiting factor in the production of biogas from animal manure is the availability of water. Water is needed for both animal consumption as well as for feeding into the anaerobic digesters [50]. However, because of climate change, sub-Saharan Africa is one of the regions hardest hit by recurring droughts and above-average temperature increases, which is negatively impacting on animal husbandry and, potentially, biogas production. The success of AD systems is intimately tied to water-to-manure ratio, making water an unarguably critical factor for optimal microbial activity and sustainable biogas production [38,64]. Inadequate water provision can induce AD-process instability, reduced gas production, and extended retention times, thereby affecting the economic viability of biogas projects [65–67]. Furthermore, fluctuations in moisture content within the feedstock can alter the microbial community composition, potentially fostering the growth of acid-forming bacteria and the subsequent deterioration of the overall biogas quality [67,68].

Addressing these intricate microbial dynamics in the wake of a water-scarcity framework is essential for optimising AD performance in SSA. Consequently, water availability for biogas production requires an effective multifaceted approach encompassing technological innovation and policy intervention [37,38]. Prospective mitigation strategies would aim at bolstering water accessibility, advocating for sustainable water management practices, and ensuring the resilience of AD systems in the face of climate variability [15,38,50]. According to [50] 60% of 700 biodigesters in Ethiopia were non-operational due to lack of water. Hence, dry savannas and desert environments require careful consideration for the functioning of biogas particularly in dry seasons [38] considering that, already, 40% of the SSA population is faced with water shortages even for drinking and cooking. To mitigate against water scarcity, induced limitations on biogas production, ref. [50] have suggested a combination of water harvesting techniques, including rainwater harvesting and storage, domestic water recycling and aquaculture. While water harvesting may ensure water availability for digesters particularly during the rainy season, thereby ensuring continuous production of biogas, it may not be easy to harvest enough water to last through both the wet and dry seasons, with the usual situation likely to be compounded by droughts. On the other hand, drawing water is already a daily chore in resource-poor settings of SSA, and the practice is made more difficult by the excessive distances travelled to fetch water for domestic use [37,38,50,69], which makes it an almost impossible supposition for poor villagers to be fetching water for biogas digesters. In another study, however, ref. [38] suggest, based on laboratory-scale biodigester experiments, a redesign of digesters to incorporate larger inlet and outlet pipes to enable use of undiluted fresh dung, which proved to produce more methane per mass of substrate compared to the currently adopted 1:1 substrate to water ratio. With further research, this approach has the potential to increase the success of anaerobic digester technology in resource-poor, drought-ravaged settings. What may be a limitation, though, is the requirement for fresh dung, which may require that livestock be penned every night to ensure substrate availability.

Holistically, however, governmental support through conducive policies and regulatory frameworks is crucial for overcoming water availability challenges in AD projects. Governments could plug this gap by investing more in water resource management, such as in the construction of dams as well as the construction of wind turbines for underground water extraction. This will not only make AD technology technically more viable but will also go a long way toward improving the quality of life owing to constant water availability. Also, governments, as custodians of policy, need to promote the adoption of biogas technology by removing policy red-tape and providing an enabling environment for public–private partnerships, which are critical for unveiling financial support for initial investments, as well as integrating water management considerations into broader energy and agricultural policies [13,37,50]. The establishment of clear guidelines for water use in AD systems, along with the enforcement of standards, can create an enabling environment for sustainable biogas production [38,50]. Collaborative efforts between governments, international organisations, and private stakeholders are essential for developing comprehensive policies that address water-scarcity challenges holistically [37,38,64].

2.3. Prospects for Future Advancements

The anaerobic digestion technology for biogas production still has room for expansion through a combination of relatively inexpensive policy initiatives and the development of new technology combinations [56]. For example, the over-reliance on fixed-dome and floating-drum digesters has contributed to the low adaptation of biogas technology in sub-Saharan Africa due to the need for large quantities of bricks, concrete, and steel, resulting in steep initial costs for poor rural households. However, there are alternative biogas technologies like the FlexiBiogas system (developed by the Kenyan Company Biogas International Limited (BIL), (Nairobi, Kenya)) which is portable and expandable, has a shorter retention time, can be transported easily and at lower cost, and does not require skilled technicians for installation, making it suitable for use in rural communities where fuelwood consumption is highest [28]. Additionally, the FlexiBiogas system can produce biogas using different kinds of feedstock such as kitchen waste, animal manure, and agricultural residue, and with dung from just one or two cows in an integrated farming system, the system can produce approximately 1.2 m^3 of biogas daily in addition to the benefits of by-products like biofertiliser, making it suitable for uptake by poor rural households [28]. Research also suggests that the use of mixed animal manure–crop residue–grass feedstocks in anaerobic digestor technology not only results in significantly increased biogas output as compared to the mono-digestion of cow dung but also goes a long way toward augmenting the otherwise insufficient manure-based feedstock [70]. Considering that rural economies are agro based, the harvesting of crop residues after a farming season will not only help in preserving them as feedstock for biogas production but will also help as cattle feed during the winter when pastures are depleted, which will help farmers to curb cattle loses. These initiatives, if adopted, may translate into more efficient anaerobic digester systems and reduce the high failure rates currently being experienced. To reduce the costs of fixed-dome anaerobic digestor systems, construction materials should be sourced locally. For instance, groups of families could form brick-laying cooperatives that would ensure that they have enough bricks for bioreactor construction as well as for sale, which could augment their income. To increase the competitiveness of anaerobic digestor systems, and to sway the preference of rural people from a firewood-based energy economy to sustainable waste-to-energy systems such as biogas, there is need for a thorough assessment of biogas technologies from both economic and environmental perspectives to better understand the trade-offs between biogas yields and the costs associated with installation and maintenance of bioreactor systems.

Another of the available low-cost biogas digester technologies is the low-cost polyethylene tube digester (Figures 3 and 4) that was developed by GTZ/EnDev project in Bolivia, which has been applied in Bolivia, Peru, Ecuador, Colombia, Centro America, and Mexico since 2010 [71]. According to [71], this kind of biogas digester costs between 93 Euro and 148 Euro as of 2010 (USD 100.94–USD 160.63, January 2024 exchange rate), and it could produce enough biogas for cooking and lighting for 4–5 h after charging it with 20 kg of cow dung or any animal dung plus 60 L of water. Furthermore, the author states that installation of this digester takes at most a day, including time spent on excavating the trench.

As technology improves, the cost of biodigesters should keep decreasing so that even poor rural households can afford them. Both the FlexiBiogas system as well as the polyethylene tube digesters are low costs initiatives, with the former having a slight advantage over the latter in that no excavation is needed for the biogas digester. Additionally, the FlexiBiogas system uses less water than the polyethene biogas digester, making it more suitable for sub-Saharan Africa where the climate is getting drier due to climate change.

Policy-wise, governments should promote public–private partnerships and incentives-based bioenergy policies that are adequately supported by action plans as well as monitoring and evaluation strategies [53]. For instance, the South African renewable energy masterplan is anchored by four pillars, one of which reads, “Building local capabilities in terms of skills and technological innovation, to enable the rollout of renewable energy and storage technologies and associated industrial development” [42]. If sub-Saharan African governments must be true to the aim of turning around the energy situation in their rural areas and to adopting carbon neutral clean energy systems, then skills development must be aggressively pursued as it is one of the cogs that drive the transformation of policy into practice.

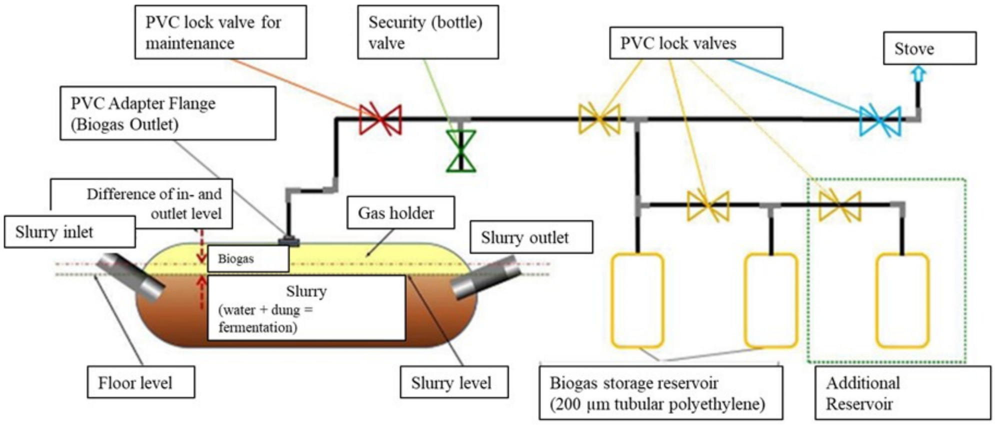

Figure 3. Schematic diagram of a low-cost polyethylene tube biogas digester, complete with biogas supply lines [71].

Figure 4. Open and closed trench for a tube digester in the Bolivian Altiplano [71].

To increase the uptake and feasibility of the anaerobic biogas digester technology in rural areas, research should also be directed at enhancing biogas output. To that end, several research studies have been conducted to assess the effectiveness of applying 'accelerators' to the anaerobic digestion tanks/bags in increasing biogas output. The study by [72] found that supplementation of a manure slurry with 2% by weight (wt%) of metal-oxide (iron oxides (30–45%)—including magnetite (Fe_3O_4) and hematite (Fe_2O_3), carbon (char or coke fines, 8–20%), and other metal (Na, Mg, K, Al, etc.) oxides)-rich bag-filter-gas dust from an iron processing plant resulted in a 51.3% increase in methane yield as compared to the control digester. They attributed the increase to the improved electron-transport capacity of the anaerobic digester, resulting in increased redox potentials. These observations of Wang et al. corroborate the findings of an earlier study by [73] who observed increased biogas production as well as shortened digestion periods when the substrate was supplemented with iron (Fe) salts, including $Fe_2(SO_4)_3$, $Fe(NO_3)_3$, $FeCl_3$, and $FeCl_2$. The use of iron filings to maximise biogas production from cow dung was corroborated by [74], who observed that supplementing a cow dung and jatropha-fruit-exocarp mixture with 10 g of iron fillings resulted in the production of 586 mL of biogas/day from a 1000 mL slurry as compared to 77 mL of biogas from 1000 mL of cow dung alone. However, while the results were positive for iron fillings, iron oxides, and/or iron salts, a study by [75] revealed that using zinc oxide nanoparticles as feed additives in an anaerobic digester reduced methane production by at least 84.55% owing to a reduction in the abundances of functional bacteria in the families *Ruminococcaceae* and *Lachnospiraceae*, as well as a massive 96.82% reduction of bacteria in the *Methanothermobacter* genus leading to poor fermentation and methanogenesis, respectively. In yet another promising study, however, ref. [76] observed that adding carbon materials as additives in anaerobic digesters significantly increased biogas yield by as much as 30–70%, an observation that they attributed to increased methanogenesis because of the conductive properties of carbon that facilitate direct interspecies electron transfer between fermenting bacteria and methanogens. While these research studies point to more efficient anaerobic digester systems that can result in more biogas being produced from the same amount of substrate compared to non-supplemented digesters, they may not be suitable for recommendation to poor rural households since this may become an additional cost to them. That said, further research needs to be performed into how to improve anaerobic digester efficiency while bearing in mind poor-resource settings.

3. Conclusions

The scrutiny of animal manure as an alternative bioenergy resource in rural sub-Saharan Africa reveals a multifaceted tableau of insights, opportunities, challenges, and an auspicious outlook. While animal manure can be directly burned to produce heat energy, this not only leads to inefficient utilisation of the resource but also results in indoor air pollution leading to a plethora of respiratory health complications. The cleaner and more efficient option, therefore, is to use animal manure as feedstock for the generation of biogas using anaerobic digester (AD) technology. Theoretically, the sub-Saharan Africa region has adequate livestock to produce enough manure to feed biogas digesters for the generation of clean energy. Pragmatically, however, the uptake of AD technology in sub-Saharan Africa is very low compared to developing nations of Asia, and therefore the existence of renewable resources has not been fully exploited for the betterment of people's livelihoods in this region. While international collaborators have helped to kick-start AD technology in SSA, this initiative has not been met with commensurate policy frameworks, and this combined with a lack of skilled technicians, lack of funding, inefficient feedstock utilisation, season drought leading to lack of water, and the inability to repair damaged biogas infrastructure among other factors has resulted in a near collapse of the African Biogas Initiative. Additionally, research-level successes have not been translated into on-field practice. There is a need to close the gap between research-level knowledge and practical, on-field implementation that requires implementation of facilitative rather than prohibitive policies, investment in technical training, and the raising of awareness of the benefits of biogas, especially among rural communities, in order to tap into the transformative capacity of animal manure as a clean bioenergy resource for sustainable energy development.

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