Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal

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Abstract

Biogas technology has the potential to provide benefits to three priority areas in Sub-Saharan Africa (SSA): energy supply, sanitation, and food security. Despite this, uptake of biogas systems has been slow and sporadic in the region. This review paper investigates what has prevented widespread dissemination of the technology in SSA by looking at the key barriers in the region, as well as identifying the main opportunities and the lessons that can be learned from successful biogas dissemination experiences in Rwanda, Tanzania, China, India, and Nepal. Installation costs, limited awareness and training for biogas users and insufficient follow-up services were recognised as being among the key barriers. SSA has favourable conditions for biogas technology, namely a suitable tropical climate in most parts of the region, a dominance of agricultural activities, and interest in alternatives to expensive conventional energy services. The region's favourable conditions therefore provide opportunities for increasing uptake of the technology. Experiences in other regions highlighted the importance of the government in supporting the biogas sector through suitable policies and incentives. Collaboration between research institutions, governmental departments, and biogas users, both current and future, was also recognised as being vital to improve the technology's dissemination and appropriate, long-term use.

Keywords:

Biogas; Anaerobic digestion; Sub-Saharan Africa; Sustainable development; Dissemination program.

1 Introduction

The current energy situation in Sub-Saharan Africa (SSA) is characterised by an abundance of resources, yet largely underdeveloped with a lack of appropriate domestic distribution and accessibility [1-3]. The majority of SSA countries struggle to meet their energy demand and rely on fuel imports, which are costly, therefore being detrimental to the economies of the countries, particularly those that are landlocked [2, 3]. Furthermore, the average electricity price in SSA is commonly two-times that of other developing regions, with an additional cost associated to an unreliable supply [4]. The limitations of electricity supply and distribution infrastructure has left 620 million people in the region without access to electricity [5]. Rural SSA populations in particular have low electrification rates – approximately 11% – and rely heavily on diverse biomass resources, such as cow dung, crop residues, fuel wood, and charcoal [6]. These resources, in turn, have negative health and environmental impacts. The majority of households are poorly ventilated, yet use traditional open fire stoves, which propagates a build-up of smoke, particulates, carbon monoxide, sulphur, and nitrogen oxides in the home, thus posing serious health risks to its inhabitants [7, 8]. The International Energy Agency (IEA) estimates that 75% of the SSA population –close to 730 million people –do not have access to clean cooking facilities [5,9]. Exposure to indoor pollution from the unimproved stoves is strongly linked to a number of diseases, including pneumonia and acute infections of the lower respiratory tract for children under the age of five, and chronic obstructive pulmonary disease in women [10]. In 2012, the World Health Organization (WHO) estimated that 581,300 people died in Africa from diseases that have been caused by exposure to indoor air pollution [6]. Aside from health impacts, the adverse effects from collection and use of these fuels on the environment and socio-economic development include: deforestation, land degradation in dry lands, aggravated soil erosion, and, associated flooding [1, 11-13]. Improved energy services, including more efficient energy sources and conversion technologies, can make a positive contribution to both the livelihoods of the SSA population and the environment [14, 15].

Biogas technology inherently meets most of the key requirements for addressing the energy access issues in SSA, and can be applied wherever there are sufficient organic materials. Biogas is comparable to natural gas due to its high methane content (50-70%), and can be used in the same way – for cooking, heating, electricity generation, and as a transport fuel [16, 17]. It has an energy content of 21 -23 MJ/m^3, is odourless, colourless, and burns with a clear blue flame [16, 18]. On an industrial level, biogas can also be fed into the natural gas grid, which occurs in some European countries, including Denmark, Switzerland, Sweden and Germany [16]. Biogas technologies are flexible in design and scale, ranging from simple household systems to high rate digesters, which are used for industrial wastewater treatment [19]. In developed regions, biogas systems commonly use a mixture of livestock manure and crop/food waste or energy crops for combined heat and power (CHP) production [20]. By contrast, biogas technology in developing regions is commonly utilised through small-scale systems, which are made from local materials or are prefabricated, as is the growing trend [21, 22]. Cattle manure and/or latrine waste are used as the main feedstock; however, there is increasing interest and development of biogas systems suitable for treating organic solid waste [20]. At these smaller scales, the technology can be integrated into household, community, or commercial organic waste management systems for improved sanitation, as well as nutrient recycling [23, 24]. Consequently, biogas technology has the potential to play an important role in improving energy access in the development process in SSA, particularly in rural regions [2, 25-27]. SSA has significant potential for biogas production from municipal organic solid and sewage waste, as well as agricultural residues [28, 29]. This is particularly important in major cities that have limited infrastructure to safely manage waste, and can convert a 'problem' into a profitable, recyclable product [17, 28]. At the rural household scale, successful biogas technology adoption can reduce or eliminate the need to collect firewood for cooking, to provide a clean alternative, while improving sanitation, and providing the potential to increase soil fertility and crop productivity through accelerated processing of organic wastes [30].

Biogas technology is unique to other renewable energy sources. It can provide benefits to three sectors that are priority areas for SSA: energy supply; sanitation, and; food security (crop productivity). In light of such benefits, this review poses the question: what has prevented widespread dissemination of this technology in SSA? Compared to Asia, the dissemination of biogas in SSA has been slow [22]. Mwirigi et al. [31] have identified cattle population, maturity of biogas programmes, and construction costs as key contributors to lower installation rates in SSA compared to Asia. The same paper provides an overview of the socioeconomic barriers of the large-scale adoption of small-scale digesters in SSA, and explores factors that could improve dissemination [31]. We provide a literature review of the financial, technical, social-cultural, and institutional barriers to biogas dissemination (both small-scale and community scale) in SSA. Key opportunities to improve sustainable biogas technology adoption in SSA are identified using general examples from SSA, specific examples from Rwanda and Tanzania, and through lessons learned from China, India, and Nepal. The final result of our paper points to the technical, economic, and policy and social strategies recommended for application in SSA countries to improve biogas dissemination.

2 Overview of biogas dissemination in SSA

Since its first introduction in the 1950s, interest in biogas technology in SSA is a resurging phenomenon, yet its uptake has been sporadic. The launch of the "Biogas for Better Life –An African Initiative" in 2007 aimed to offer investment and business opportunities, market-orientated partnerships, and local ownership, with 2 million biogas installations by 2020 [32]. The initiative represented the first instance that the potential of biogas was evaluated for the whole continent of Africa, and provided a platform for biogas dissemination programmes in SSA through establishing the Africa Biogas Partnership Programme (ABPP). The ABPP is a partnership between two Dutch non-profit organisations, Hivos and the Netherlands Development Organisation (SNV), which currently supports domestic biogas programmes in five SSA countries: Burkina Faso, Ethiopia, Kenya, Tanzania, and Uganda [33]. The programme aims to install 100,000 biogas plants to provide sustainable energy to half a million people by 2017 [33]. In June 2013, a total of 29,500 biogas digesters were installed since the programme's commencement in 2009 34]. The domestic programmes focus on households that have four or more cattle to provide dung as feedstock, making them less accessible to those with a lower socioeconomic standing, due to cattle ownership being linked to status and wealth in SSA [28]. In addition to the five countries currently running domestic biogas programmes through ABPP, several other SSA countries have experience with biogas technology, including: Benin, Cameroon, Lesotho, Madagascar, Nigeria, Rwanda, Senegal, South Africa, and Zimbabwe [17, 28, 35, 36]. The oil crisis in the 1970s, along with the success of biogas use in China and India, motivated many of these countries to start development programmes for the technology, which involved scientific, technical, social and economic studies [36]. The studies were carried out precipitously and, as a result, brought disappointment, leading some administrators to believe that biogas is unsuitable for SSA [36].

2.1 National examples of biogas dissemination in SSA

2.1.1 Biogas in Tanzania

Biogas technology was first introduced in Tanzania in the 1970s. The Small Industries Development Organisation (SIDO), a parastatal organisation, installed floating-drum biogas digesters in the country between 1975 and 1984 [37]. During this time, the Arusha Appropriate Technology Project also began installing biogas systems (floating-drum and Chinese fixed-dome models) in the Arusha region [37]. In 1982, the Centre for Agricultural Mechanization and Rural Technology (CAMARTEC), a government research organisation, was established, who continued the dissemination of biogas technology in Arusha [37, 38]. CAMARTEC, together with the German GTZ, then set up the Biogas Extension Service, which disseminated biogas plants in the coffee and banana growing regions of Arusha until 1994 [37]. Widespread use of the technology, however, did not occur until the Tanzania Domestic Biogas Programme (TDBP) was implemented under ABPP in 2009 [39]. TDBP is a partnership between SNV, Hivos and CAMARTEC, and aims to develop a commercially viable domestic biogas sector that will help improve the livelihoods of rural Tanzanian farmers [39, 40].

Training and accreditation for biogas masons is provided through short-term biogas system construction and supervision courses at regional training institutes [39, 40]. Masons are encouraged to form informal associations and working groups to enable them to become private-sector based biogas service-delivery providers [39]. The programme initially set a target of 12,000 biogas installations by the end of 2013 [37]. While this target was not achieved, with total installations since 2009 only reaching 8,796, the actual installations for 2013 exceeded the target for the year [41]. Tanzania therefore has a relatively successful domestic biogas sector as the adoption of the technology continues to grow.

Tanzania has a number of favourable conditions for biogas dissemination which have contributed to its relative success. The country's climatic conditions are well suited for biogas technology use, with average air temperatures ranging between 26.5°C to 30°C [35, 42]. Its current energy situation calls for a shift from the dominant reliance on traditional biomass (over 90% for cooking, heating, and lighting) to more sustainable options [37, 38]. Demand for firewood has been increasing while wood resources are declining [38]. The scarcity of firewood, along with the large number of households with indoor-fed cattle and/or pigs in some parts of Tanzania, has enabled biogas to become an attractive and suitable technology [38]. The Tanzanian government has been supporting most of the biogas projects in the country, providing funding in collaboration with donors, as part of its key policy objective to increase access to affordable and reliable energy services, and stimulate productivity [38]. CAMARTEC has been a key driving force in developing biogas technology for application in Tanzania and other parts of Africa. Its modified Chinese fixed dome design, the CAMARTEC design, is being adopted by the Tanzanian private sector, under the TDBP as well as in other African countries [37, 43]. The organisation has experience with providing training for technicians on biogas system construction, and instructing users, particularly women, on system management and operation, as well as advising on the use of slurry, gas pipeline systems, burners, and lamps [38]. Aside from the TDBP, a number of other biogas projects have been set up in Tanzania, including Biogas support for Tanzania (BiogasST) and the Best Ray project –Bringing Energy Services to Tanzanian Rural Areas – which has contributed to the use and development of the different types of systems [40, 44]. This wide knowledge base in biogas system types has enabled biogas technology to be applicable to different contexts throughout Tanzania.

While the uptake of biogas technology has been increasing in Tanzania, the country still faces a few challenges for its widespread dissemination. The key barrier of high installation and maintenance costs is evident in the way dissemination has been focused in the northern part of the country as well as the capital, Dar es Salaam, where there are large livestock numbers and relatively higher income levels [38]. A study conducted in the Rungwe district showed that households are willing to adopt biogas technology but are held back from doing so due to being unable to meet the costs [38]. Other challenges experienced with different types of biogas systems in Tanzania include: inadequate water availability; more expertise required in construction and maintenance; low awareness about the technology and potential feedstocks; low level of understanding on appropriate operation due to insufficient operating instructions; poor performance of the system due to a lack of maintenance; limited or no follow-up services provided by installer; and; use of biogas limited to cooking [38, 42, 45].To overcome some of these challenges, it has been recommended that more technicians are employed and trained to provide follow-up services, including inspections and repairs, particularly in the first few months after the systems are installed [38, 42]. Other recommendations include: preparing and distributing simple operation and maintenance manuals in English and Kiswahili (as has already been done in some areas); encouraging users to contact installers immediately when problems arise; and; including additional gas connections for heating and lighting in the installation [38, 42, 46].

Tanzania has experienced a number of benefits from the use of biogas, particularly through its contribution to reducing wood fuel and kerosene consumption, and the negative effects associated with their use for household cooking and lighting [38, 45, 46]. The integration of cattle raising and farming with biogas production has contributed to increasing the income of farming households [38]. The biogas sector also offers potential for increased employment opportunities [38]. A study conducted in two Tanzanian villages found that the adoption of biogas technology has brought about significant changes to the division of labour within households [45]. In more than half of the households in the study, the men have taken on the responsibility of collecting the feedstock(s) for biogas production, which has largely replaced firewood collection, a task that was predominantly assigned to women [45]. The responsibility of cooking also transitioned in just over half of the households from being solely the mother's responsibility, to it being equally shared between the father and mother and, in the remaining surveyed households, the task of cooking was found to be shared by all household members, after the biogas system installation [45].

2.1.2 Biogas in Rwanda

Compared to Tanzania, biogas technology has had a relatively short history in Rwanda, with the government promoting it as an alternative energy for cooking and lighting since the late 1990s, and the first systems being installed in 2001 [47, 48]. The Kigali Institute of Science, Technology and Management (KIST) began developing and installing large scale biogas plants through its Centre for Innovations and Technology Transfer (CTT) to address the issue of sewage disposal in overcrowded prisons in the aftermath of the genocide [49, 50]. The first system installed was a 600 m^3

community-scale biogas plant at the Cyangugu prison, which used toilet waste from 1,500 prisoners as the main feedstock and supplied half of the 6,000-inmate prison's cooking needs [48, 51]. By 2008, 28 community-scale biogas systems were in operation in Rwanda and 8 more were under construction, including: 13 in secondary schools, 11 in prisons, seven in community households, two in military camps, two in training demonstration centres, and one in a hospital [48]. Household-scale systems were introduced into the country through the National Domestic Biogas Programme (NDBP), implemented in 2007 by the Rwandan government in partnership with SNV and the German Development Organisation, GIZ [52]. The programme's main aim was to "establish a sustainable and commercial biogas sector in Rwanda" to reduce the depletion of biomass resources in the country, while also improving the quality of life of Rwandan families [53]. The government recognised biogas technology as an important part of improving the country's energy supply, reducing waste, and addressing environmental problems [50]. Strict tree cutting monitoring and zero-grazing policies were also implemented, which indirectly favoured biogas use [50]. Under the NDBP, 2,600 family-sized biogas systems had been installed by August 2012, which was well below the initial target of 15,000 and the revised target of 5,000 systems by 2011 [52].

The main barriers of biogas dissemination in Rwanda are financial, technical, social-cultural or institutional. Key financial challenges are potential biogas users being unable to afford the installation costs with subsidies being limited and loans from banks being difficult to obtain, as well as firewood being considered as a cheaper energy source [50, 52]. The short term history of the technology's use has presented social barriers due to uncertainties about its costs and benefits to the user, and, since some of the key benefits are indirect, they are not recognised by the user [52]. The strict modelling and favour of the NDBP on a single type of household-scale biogas digester is also preventing systems being designed and tailored to local needs [50]. Significant institutional barriers are present in Rwanda mainly due to: limited technical capacity from a largely unskilled workforce and few entrepreneurs; limited governmental capacity and budget for research and development, as poverty and food security issues take precedence; limited infrastructure, making access to rural areas for construction difficult; lack of collaboration between public agencies and private sector (technology research centres and training institutes are marginal partners in the biogas programme); and; a need for greater unity among biogas companies [50, 52].

Despite these setbacks, Rwanda has done well to promote and launch a biogas industry in a short amount of time, given its limited resources and technical capacity. Rwanda stands as a unique example in SSA of the successful use of community-scale biogas systems. The use of large biogas systems in Rwandan schools, prisons and community households has resulted in financial, social (health) and environmental benefits. In eight of the prisons with biogas systems installed, an average saving of 19% of firewood use was achieved, which could be raised to 30% with some minor technical and management improvements [48]. Community households experienced the greatest reduction in firewood consumption – over 80% in some instances – with biogas being able to meet all of the cooking energy needs, providing financial cost savings that deliver high returns, reducing/ eliminating odour, improving hygiene, and reducing indoor pollution [48].

2.2 Biogas dissemination and challenges in China

China is the largest biogas producer and consumer in the world with between 30 to 40 million domestic scale biogas plants installed all over the country [28, 35]. Over the past forty years, the focus has been on utilising biogas to supply energy and help alleviate environmental stresses in rural regions with household-scale systems, while interest and application of medium to large scale systems has been increasing rapidly since the early 2000s [53-56]. The long history and consistent use of the technology in the country has enabled it to become well-developed, complete with standards for rural biogas system design, construction, operation, and facility production, as well as integrated utilisation patterns in agricultural production and engineering structures for appropriate installation [53]. Biogas technology for rural development has been strongly supported by the Chinese government over the past forty years [35, 56]. Since 1986, the government has been introducing and implementing energy policies that support the development and increased use of renewable energy, including biogas [56]. The country has 40,000 full-time staff members working in 8,000 rural energy offices in over 1,900 counties and towns to oversee the administration of biogas in rural areas with education, advocacy and training provided by the Ministry of Agriculture [35]. The biogas sector in China saw a rapid rise from the early 2000s up to 2010, due to the government providing support for the construction of rural household digesters, as well as some medium and large-scale systems, known as the "National Debt Project for Rural Biogas Construction" [35, 56]. The widespread use of biogas technology has led to employment in a number of areas including: manufacturing of biogas equipment and appliances; research and development; rural energy management and technology promotion; quality supervision and inspection; training and vocational skills certification; and services for biogas users, such as construction, operations management, maintenance, and repair [54]. China still has significant potential to increase its biogas use, with the installed household-scale systems accounting for just over 30% of the total potential, and less than 2% of the potential agricultural organic waste currently being exploited [54]. The challenges facing the biogas industry in China include: systems being underutilised or abandoned due to migration of rural labour to the cities; popularisation of commercial energy use; decline in backyard farming and unstable supply of feedstock due to fluctuations in livestock breeding; technical problems due to faulty or low quality materials and insufficient product support; lack of training and follow-up for farmers with household systems, leading to poor operation and maintenance; and weak demand as the integrated benefits, particularly direct economic benefits, have not been realised [54, 56]. A number of household digesters, particularly those built prior to the 1990s, failed, as many of these systems were unheated and led to low or unstable biogas production, especially in Northern China, where the mean temperature is between 10 and 15°C for around half of the year [56]. This problem is unlikely to be faced in most parts of SSA due to the warm climate.

2.3 Biogas dissemination and challenges in India

India is another major biogas producer, with the number of total installed systems being 4.5 million in 2009 [57]. Like many other developing countries, India has a limited conventional energy supply and is heavily reliant on fuel wood as an energy source for cooking, especially in rural regions, but this resource is becoming increasingly scarce [58]. Development of biogas digesters commenced in India in 1939, with the first plants constructed on a mass scale for dissemination in 1960 by the Khadi Village Industries Commission (KVIC) [59]. The National Programme on Biogas Development (NPBD) was implemented in 1982 with the aim that biogas could supply all the cooking energy requirements for rural households, and it is now one of the two largest biogas programmes in the world, the other being in China [58]. Substantial subsidies under the programme between 1985 and 1992, enabled biogas to become a well-established technology with dissemination continuing even after the subsidies were reduced [60]. The successful dissemination also boosted development of variations of floating cover and fixed dome systems, with at least seven different types being approved for the NPBD by the Ministry of Non-Conventional Energy Sources [60, 61]. By the early 2000s, however, target-driven dissemination led to unhealthy competition between the implementing agencies, resulting in: lower standards of construction and materials, eligibility and sustainability criteria being overlooked, inconsistencies in the reporting of achievements, and a lack of follow up services and accountability for maintenance [58, 62]. To address these issues, the government merged NPBD with the manure management initiative in 2005 to form the National Biogas and Manure Management Programme (NBMMP) [62]. Other challenges faced in some areas include: limited awareness and education for biogas users on how to maximise the benefits from their system; lack of training and follow-up services, particularly for female biogas users; and high installation costs or insufficient supply of cow dung, hindering some rural families from adopting the technology [58, 62, 63]. One district of India, Uttara Kannada, particularly the Sirsi block, has experienced a high success rate with all of the installed biogas plants remaining in operation [58]. Sirsi has favourable conditions for biogas dissemination due to the users having a high level of interest in and awareness of the technology, along with a high literacy rate, possible higher income, easy credit access from multiple agencies, no access to some conventional fuels, relatively large cattle holdings, strong government support, awareness of forest conservation due to regional conservation and afforestation programmes, and good services provided by installers [58]. The installed systems were found to provide sufficient gas for cooking and high quality fertiliser in the majority of households [58]. The Indian government and local organisations such as KVIC have therefore been essential to the widespread use and development of biogas technology in the country.

2.4 Biogas dissemination and challenges in Nepal

The energy supply situation in Nepal can be likened to that in many SSA countries. Fuel wood, agricultural residues and animal waste are the dominant energy resources in the country due to a low electrification rate, lack of fossil fuel resources, and, therefore, a reliance on expensive fuel imports [24, 64, 65]. The use of these traditional biomass resources has caused many of the same environmental, social (especially in relation to health) and economical concerns currently facing SSA, including significant damage to forests [24, 65]. In response, the Nepali government initiated the production and distribution of renewable energy technologies, with biogas being recognised as a particularly viable technology, as it proved to be feasible within the socio-physical conditions of the country and offered several environmental, agricultural, economic and health benefits [24, 64]. Nepal has seen a successful development of its biogas sector with over 260,899 installations by 2012 [66]. Its success has been attributed to seven main factors: increasing level of awareness of the benefits among the rural population; energy, health and environmental costs associated with traditional energy sources; inaccessible and underdeveloped rural communities with little or no modern fuel supplies; abundant organic waste supplies on farms for use in biogas systems; technology available freely, without intellectual property rights issues; readily available raw construction materials; and the availability of loans and subsidies from the government [67]. The technology was first introduced to the country in 1955 but large scale use did not occur until the establishment of the Biogas Support Program (BSP) in 1992 [24, 67]. The BSP is a working partnership between governmental institutions of Nepal, Dutch and German development organisations, the private sector in Nepal and rural Nepali farmers [67]. The government of Nepal has been a particularly strong advocate for biogas, having implemented initiatives to support promotion and development of the technology since 1974 [68].

The main challenges facing the biogas sector in Nepal are: cold temperatures in many of the country's hilly areas, making conventional biogas systems unfeasible there; need for greater private sector capability for biogas system installations; remote locations of many villages, making implementation of the systems difficult; the technology still being too expensive for some rural households which are excluded from government subsidies; lack of adequate water supplies to operate biogas plants in hilly and mountainous regions; and increased mosquito prevalence reported by biogas system users after installation, also causing adverse publicity of the technology [24, 68, 69]. However, biogas technology has also contributed to increasing the socio-economic status of its users in Nepal. The main recorded benefits are: a reduction in the workload and time spent on household activities, with women as the main beneficiaries; improved health for families due to reduced indoor smoke and air pollution from the replacement or reduction of firewood and dung cake use, especially for cooking; improved sanitation levels through connecting a toilet to the system; increased productivity in crops and kitchen gardens, leading to increased incomes; replaced use of raw dung and chemical fertilisers on crops; and employment for 13,000 people under the BSP [24, 66, 67]. The benefits of biogas identified in Nepal demonstrate the realisable benefits of biogas for SSA due to the region also having a large rural population dependent on agriculture.

3 Discussion

3.1 Main barriers to biogas dissemination in SSA

The main barriers to biogas dissemination can be categorised as financial, technical, social-cultural, or institutional, as shown in Table 1. The installation costs of conventional biogas systems present a significant barrier to increased adoption of biogas technology, particularly in rural regions. Many farmers and rural households have seasonal incomes and, of the revenue generated, only a very small portion is disposable [51]. Flexible credit schemes are also hard to come by, both for those seeking to install biogas systems and for entrepreneurs wanting to set up biogas installation and maintenance businesses. A survey conducted in Uganda found that households with a higher income were more likely to adopt biogas technology, and all the surveyed households with biogas systems had the assistance of donor agencies for the installation [43]. The installation costs of household systems under domestic biogas programmes in SSA were found to be higher than similar programmes in Asia, including the Nepali BSP [31]. Governmental or donor agency support for the installation of biogas systems is not uncommon in SSA and leads to uncertainty over the ownership and maintenance responsibility of the system [43, 51]. The biogas user, who has paid a minimum amount for the installed system, often views it as being externally owned and expects government/donor support for maintenance. In many instances, however, technical support or sufficient training for the biogas user has not been provided by the biogas installer/promoter and many systems break down or are abandoned [35, 51, 70, 71]. Poor design choices, mainly due to overlooking the user energy needs and local conditions, are another major contributor to the short lifespan of many installed biogas systems [35, 36, 70, 71]. The energy needs of the potential biogas user need to be considered when dimensioning the system, while the amount, seasonal availability and ease of collection of both water and the feedstock material/s can be used as indicators to make appropriate design choices.

A well designed biogas system is of little use if it is not socially or culturally acceptable. The inertia to change from traditional firewood stoves to biogas stoves in SSA has been great in some areas due to the perception that food cooked the traditional way with firewood, tastes better, or that the biogas flame is small and cooking is slow, as well as the biogas stove not always being suitable for cooking traditional food, which requires several hours of cooking on the stove [17, 36, 70]. Firewood collection for household energy is a social activity in some areas – for women in Burkina Faso, for example – if firewood is replaced with biogas, an alternative social activity needs to be sought [70]. In other regions, firewood collection is an important source of income for use in charcoal production or to sell firewood to others directly. While some regions are used to using animal dung for energy generation, others, such as in Zimbabwe, do not consider it to be acceptable to cook food from energy generated from animal dung [36]. It has also been suggested that traditional gender roles in households can present a challenge to biogas adoption, as often the decision to invest in a biogas system rests on the man that is generally the head of the household, while the women and children would be the ones receiving the most benefit from it because they would use the technology for cooking [31, 70]. Many of these social barriers can be overcome through considering social and cultural factors in the design of systems, as well as communicating effectively with potential biogas users on the appropriate use and benefits of biogas technology to help meet their needs. The transfer of knowledge and information regarding biogas technology, however, can be more challenging in some parts of SSA due to a high illiteracy rate [17].

SSA is currently experiencing a gap in appropriate government policies and institutional support, which are important for successful biogas dissemination. Strategies that national, state and local governments can implement to help increase the uptake of biogas technology in SSA include: appropriate financial incentives, such as loans and subsidies; educational and promotional campaigns; institutional frameworks to coordinate and stimulate interaction between stakeholders in the biogas industry, as was suggested for Uganda; regulatory authorities to coordinate research and development activities; standards and codes of practice; and a development and funding agenda for research and development [17, 31, 43, 72]. SSA also faces the challenge of a low population density compared to developing regions in Southeast Asia, India, and China, where biogas technology has been successful [35]. An increase in collaboration and knowledge sharing is therefore required within and between SSA countries, as well as internationally with countries that have had a successful biogas uptake, to provide the necessary translational research and capacity building for biogas technology that is suited to the SSA context.

Table 1: Main barriers to biogas dissemination in Sub-Saharan Africa

Type	Description	Reference
Financial	• Installation costs for conventional biogas systems unaffordable for many potential users with limited or no disposable income	[17, 31, 36, 43, 51]
	• Lack of flexible credit schemes and other financial support for potential biogas users and entrepreneurs to set up biogas businesses	[31, 51]
	• Competition from firewood –where wood collection is free and available	[36, 70]
Technical	• Lack of local system performance documentation; result of short term use	[17]
	• Low rate of functional installed biogas systems/short lifespans	[35, 70]
	• Gas leaks and cracking in digester	[70]
	• Lack of local capacity for maintenance	[70]
	• Incorrect operation and lack of maintenance due to lack of technical skills (especially in rural regions) and inadequate training and follow-up	[35, 51, 70, 71]
	• Poor design and construction: unsuitable for local conditions and/or users	[31, 35, 36, 70, 71]
	• Lack of water supplies or permanent water supplies	[35, 51, 70]
	• Reliance on expensive imported construction materials and spare parts	[36, 51]
	• Insufficient substrate and/or time and money	[35, 36]
Social-cultural	• Preference of cooking the traditional way, with firewood stove instead of with biogas stove	[17, 70]
	• Inertia towards change and new technology	[17]
	• Competition with traditional/other uses of feedstock materials such as cow dung	[36, 70]
	• Social/cultural/religious objections to using animal or human waste	[36]
	• Rearing of cattle and other livestock carried out in open fields/animals allowed to wander, making dung collection for biogas unfeasible	[17]
	• Biogas technology adoption may require a change in the traditional energy use decisions: women and children of a household most likely to use the biogas system while men are most likely to make investment decisions	[70]
	• Low literacy levels make adoption of the technology more difficult	[17]
	• Lack of awareness about the technology and its benefits	[2, 31, 52, 70, 73-75]
Institutional	• Insufficient government support or biogas policies	[2, 31, 35, 51, 74]
	• Low population density	
	• Ownership and responsibility of biogas system not well defined/understood	[35, 43, 51, 70]
	• Lack of up to date information, knowledge sharing, and translational biogas research at national, continental, and international scales	[51, 71]

3.2 Main opportunities for biogas dissemination in SSA

SSA has a number of favourable conditions for the use of biogas technology. The region is dominated by a tropical thermal climate, with an average monthly temperature above 18°C for the entire year, which is well suited for anaerobic digestion [35, 76, 77]. Livestock rearing is practiced throughout

SSA and provides a significant potential for biogas production from animal excreta, particularly if the livestock is zero-grazed or kept overnight in cattle camps, as is commonly practiced in countries like Kenya, Malawi, South Sudan, Tanzania, and Uganda [43, 46, 51, 78]. The increasing prices of fossil fuels and fertiliser have helped make biogas an attractive alternative for energy and fertiliser production in some SSA countries, for example Burkina Faso [70]. Increasing prices of fuel wood and other energy sources for cooking, as well as expensive lighting costs when using kerosene, has also prompted interest in biogas as a cheaper, cleaner, and more convenient alternative [43, 51].

The benefits of biogas to SSA are wide reaching over the three main pillars of sustainability: economic, social, and environmental, as outlined in Table 2. The use of biogas systems that can be produced from locally available materials, including most fixed dome, some floating cover and tubular digester designs, assists in reducing the dependence on and need for aid, construction and spare parts, along with creating jobs and encouraging technical skills to be acquired locally [2, 28, 36, 51]. The implementation of biogas systems also helps to improve energy security and reduce reliance on expensive liquid fuel imports by providing a stable, decentralised energy supply from local, renewable sources [36]. Biogas produced from agricultural residues, industrial and municipal waste/wastewater is an attractive option in developing countries, as it does not compete with food crops for land, water and fertilisers, unlike other bioenergy sources, such as bioethanol and biodiesel [79]. Food security and nutrition can also be increased through the use of the biogas output slurry on household vegetable gardens or food croplands [51]. Improvements to sanitation and organic waste management practices in SSA can be made by directly feeding animal excreta into biogas digesters and connecting latrines to household and community scale plants, as well as treating the large amounts of waste/wastewater from food processing facilities [70]. Retrofitting household septic tanks into biogas generators has been identified as a solution to address the waste management issues in the Nigerian capital of Lagos, which has a dense population and a low quality sewage system that leaks directly into the city's drainage system [80]. Further social benefits of biogas use are gained through its use as a clean, smokeless cooking fuel, reducing indoor pollution and the risk of smoke-related diseases; while also easing the burden on those responsible for fuel wood collection, predominantly women and children, allowing more time for productive activities or attending school [36, 43].

Table 2: Benefits biogas technology can provide in Sub-Saharan Africa

Type	Description	Reference
Economic	• Reduced aid dependence through local construction and materials	[2, 36]
	• Low cost energy for cooking and lighting	[43, 51]
	• Creation of jobs and technical skills	[51]

Social	• Improved energy security and reduced fuel imports	[36]
	• Improved food security through use of biogas slurry as fertiliser	[36, 51]
	• Improved sanitation, particularly through safer handling of wastes	[70]
	• Improved health through provision of clean, smokeless fuel	[36]
	• Enhanced productivity of women and eased labour burden	[43]
Environmental	• Sustainable source of energy and fertiliser, helping to enhance soil fertility and maintain the natural nutrient cycle	[36, 70]
	• Encourages prevention of overgrazing	
	• Improved waste and wastewater management	[28, 70]
	• Reduced risk of deforestation and land degradation	[36, 43]

3.3 Key recommendations for improving biogas dissemination in SSA

The recommended strategies for improving biogas dissemination in SSA range from technical, economic, policy and social, as summarised in Table 4. Improved designs of biogas systems and associated appliances, tailored to the specific needs and conditions of the user, including: energy requirements, feedstock availability, local building materials, environmental conditions, budget, etc., is the main technical objective. Collaboration between universities, governments, biogas companies and other stakeholders is required to firstly identify the user needs and local conditions, and then modify existing biogas system designs. The uptake and effective use of biogas systems is then likely to improve if system designs are based on user needs. The establishment of a biogas knowledge hub in SSA would also encourage further collaboration between biogas stakeholders for strengthening research and development of the technology. CAMARTEC in Tanzania and KVIC in India have shown the impact these institutions can have in driving this type of research and development through collaboration with the government. Economic incentives including: soft loans, low cost credit, financial aid for the user, direct and indirect subsidies and international funding through the Clean Development Mechanism (CDM) and Joint Implementation (JI) programme, and fee-for-service schemes, can assist in making the technology more affordable and financially attractive [17, 31, 43]. Care needs to be taken, however, that financial incentives do not contribute to the issues with ownership and responsibility. National governments can assist with setting up a policy framework that is supportive of biogas technology, as has been the case in China, India, Nepal, Tanzania and Rwanda. Appropriate standards or best practice guidelines, similar to what has been done in China, has been suggested specifically for Nigeria and Uganda [17, 43]. The standardisation of biogas digester designs, as suggested by Mwirigi et al. [31], is not recommended, as this can hinder the design of the systems being tailored to local conditions. Design standards are of particular importance for biogas appliances in SSA, specifically cook stoves, to ensure the stoves run efficiently, as incomplete combustion releases poisonous carbon monoxide and soot particles [81]. Environmental policies such as the tree cutting restrictions in Rwanda and energy policies that place emphasis on renewable energy, as is the case in China and Nepal, could be implemented throughout SSA. Many of the social-cultural barriers can be overcome through appropriate educational and promotional campaigns that demonstrate the benefits of biogas and also provide training for potential users and installers [17, 31, 43, 52]. A good example of this is the use of a biogas system in a school as a training and demonstration site in South Sudan [51]. Implementing training and demonstration sites in both rural and urban centres will raise awareness and equip local biogas users. The application of these suggested strategies is anticipated to lead to an overall increased uptake of biogas technology and improved skill to operate and maintain the systems.

Table 3: Recommended strategies for improved biogas dissemination in Sub-Saharan Africa

Area	Objective	Responsible Body	Outcomes	Recommended Action
Technical	• Design biogas systems that are specific to user needs and local conditions	• Universities and other research institutes • National, state, and local governments • Biogas companies and entrepreneurs • Non-governmental organisations (NGOs)	• Increased uptake and efficient use of biogas systems, reduced abandonment of systems, increased productive use of systems	• Modify existing biogas system designs according to identified user needs and local conditions • Establish biogas technology knowledge sharing hub
Economic	• Reduce biogas system installation cost barrier	• Biogas companies • Banks/financial institutions • National and state governments • NGOs	• Increased uptake of biogas systems among low income earners	• Provide soft loans, low cost credit • Apply for international funding e.g. CDM & JI programme • Direct and indirect subsidies • Introduce fee-for-service schemes
Policy	• Establish policy framework that is supportive of biogas technology	• National governments	• Increased uptake of biogas technology for energy supply and waste management	• National energy policies with set targets for RE • National standards and guidelines construction and operation • Biogas technology mentioned in national waste management policies/standards • Policies to restrict tree harvesting and grazing

Area	Objective	Responsible Body	Outcomes	Recommended Action
Social	• Effective long term use and acceptance of biogas technology	• National, state, local governments • Biogas companies • NGOs	• Increased awareness of the benefits of biogas • Increased skills to effectively operate and maintain biogas systems	• Training and demonstration centres located in both urban and rural regions

4 Conclusion

High installation costs, inadequate user awareness and training, as well as insufficient follow-up services are persistent barriers in biogas dissemination in Sub-Saharan Africa. The sharing of knowledge and experiences is a crucial part of ensuring biogas technology continues to be developed and applied more efficiently and appropriately in SSA. Current designs of biogas systems require improvement to suit the context and needs of the intended user in SSA. While China, India, Nepal, and, to an extent, Rwanda and Tanzania, have received government support through appropriate policies and programmes, supportive political framework and financial incentives will be a major stimulus in many SSA countries. Demonstration and training centres will also raise awareness and remove some social barriers towards biogas technology adoption to obtain the many benefits of improved biogas dissemination in SSA. Future research is recommended on the effectiveness of implementing one or more of the strategies proposed in this paper to improve the uptake of biogas technology in SSA.

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