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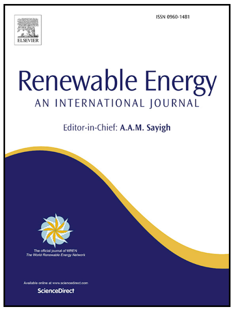

Development of an optimal biogas system design model for Sub-Saharan Africa with case studies from Kenya and Cameroon

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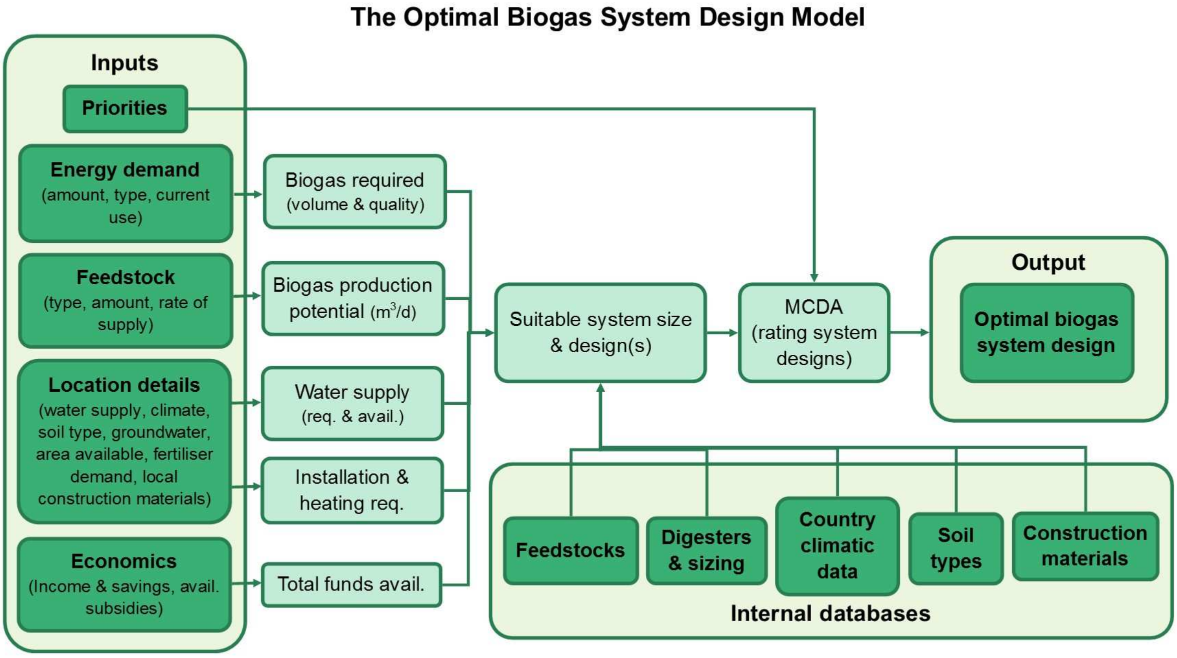
The Optimal Biogas System Design Model
Inputs
Priorities
Energy demand (amount, type, current use)
Feedstock (type, amount, rate of supply)
Location details (water supply, climate, soil type, groundwater, area available, fertiliser demand, local construction materials)
Economics (Income & savings, avail. subsidies)
Biogas required (volume & quality)
Biogas production potential (m^3/d)
Water supply (req. & avail.)
Installation & heating req.
Total funds avail.
Suitable system size & design(s)
MCDA (rating system designs)
Output
Optimal biogas system design
Feedstocks
Digesters & sizing
Country climatic data
Soil types
Construction materials
Internal databases

Development of an optimal biogas system design model for Sub-Saharan Africa with case studies from Kenya and Cameroon

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Abstract

The optimal biogas system design model (OBSDM) described in this paper is intended to be used as a decision-making tool to increase awareness of the potential of biogas technology for different applications in Sub-Saharan Africa (SSA). The decision-making tool identifies the most suitable biodigester design based on user defined inputs, including energy and fertiliser requirements; feedstock (type, amount, and rate of supply); water supply; land use (area, soil type, ground water level); climate (temperature and rainfall); construction materials available locally; and the priorities (based on sustainability criteria) of the intended biogas user. The output of the model provides a recommended design with estimates of the expected costs, energy and fertiliser production, and links to contact biodigester suppliers. In order to test the model, data from household surveys conducted in rural regions of Kenya and Cameroon were used as inputs to the model. An innovative fixed dome biodigester design, which uses stabilised soil blocks instead of bricks, was identified as optimal for both Kenyan and Cameroonian rural households. The expected performance of the optimal biogas system design from the model output was consistent with survey data on existing biogas systems in the region.

Keywords

Anaerobic digestion; biogas; Sub-Saharan Africa; multi-criteria decision making; sustainable development; rural households

Nomenclature

BMY	Methane yield for a chosen feedstock per kg of oDM
BPP	Biogas production potential
BY_{FMi}	Biogas yield per t of fresh matter
BY_i	Biogas yields per kg of oDM
d^-	Distance from the worst score
d^+	Distance from the best score
DM	Dry matter

η_{BP}	Biogas production efficiency for a given biodigester type
EPP	Energy production potential
EY_i	Energy yield in kWh per m3 of biogas produced for a chosen feedstock type
f_{CH4}	Fraction of methane in biogas
FM	Fresh matter
HRT	Hydraulic retention time in days
HRT_{dig_max}	Maximum HRT for a given digester type
HRT_{dig_min}	Minimum HRT for a given digester type
HRT_{FS_max}	Maximum HRT based on the feedstock
HRT_{FS_min}	Minimum HRT based on the feedstock
HRT_{max}	Maximum feasible HRT based on the digester and feedstock type
HRT_{min}	Minimum feasible HRT based on the digester and feedstock type
HRT_{th_max}	Maximum theoretical HRT based on the digester and feedstock type
HRT_{th_min}	Minimum theoretical HRT based on the digester and feedstock type
K	Relative substrate micro-organism constant
M	Mesophilic operating temperature range
m_i	Daily mass input of for a chosen feedstock type
μ_m	Maximum specific growth rate
MPP	Daily methane production potential
m_w	Daily mass of water available
m_{w_max}	Maximum mass of water required
m_{w_min}	Minimum mass of water required
n_{dig}	Number of digesters
oDM	Organic dry matter
OLR	Organic loading rate
OLR_{adj}	Adjusted organic loading rate
OLR_{HRT}	Organic loading rate associated with the HRT range
OLR_{max}	Maximum organic loading rate
OLR_{min}	Minimum organic loading rate
P	Psychrophilic operating temperature range
p	Temperature rate constant
s^-	Worst score
s^+	Ideal score
T	Thermophilic operating temperature range
T_a	Ambient temperature
$T_{a\text{-}max}$	Mean ambient high temperature
$T_{a\text{-}min}$	Mean ambient low temperature
T_{dig}	Digester temperature
$T_{dig\text{-}op}$	Digester operating temperature range
T_{HRT}	The digester temperature for which the HRT range was assigned
TS	Total solids
T_{set}	Set temperature of a heating system
$TS_{in\text{-}max}$	maximum TS based on the input feedstock mix
$TS_{in\text{-}min}$	minimum TS based on the input feedstock mix
V	Volumetric flowrate of the input feedstock/water mix
V_{cons}	Daily volume of gas consumed
V_{dig}	Chosen digester volume & size
V_{dig_avail}	Available digester size

$V_{dig\_avail\_feas}$	Feasible available digester volume
V_{dig_ideal}	Ideal digester volume
$V_{dig\_max,adj}$	Adjusted maximum feasible digester volume
$V_{dig\_min,adj}$	Adjusted minimum feasible digester volume
V_{dig_max}	Maximum feasible digester volume
V_{dig_min}	Minimum feasible digester volume
V_{gh}	Gasholder volume
VS	Volatile solids
w_{ij}	Weight assigned to a priority criteria score for a given biogas system design option
x	Parameter value
z	Overall weighted score

1 Introduction

Biogas technology has been recognised as an important technology to contribute to improved energy and food security, as well as treatment of organic wastes in Sub-Saharan Africa (SSA) [1-3]. While there are existing examples of biogas systems at all scales – household, community, institutional, and commercial – only household biogas technology dissemination has occurred on a larger scale through domestic biogas programmes in selected SSA countries [1, 4-6]. Increased uptake of the technology in the region is hindered by high installation costs; inadequate user training, awareness, and follow up services; and poor design choices due to overlooking the user energy needs and local conditions [7-11]. Furthermore, the energy potential of organic wastes through treatment in biodigesters and the full functions and benefits of the technology remain largely unknown to the majority of the SSA population. To help increase awareness along with assisting biogas installers, program implementers, and other stakeholders in the biogas industry, an optimal biogas system design model (OBSDM) has been developed to be used as a decision-making tool for the SSA context. The model considers a number of interacting factors, which influence the biodigester design, including the energy demand; fertilizer requirements; feedstock (type, amount, and rate of supply); water supply; land use (area, soil type, ground water level); climate (temperature and rainfall); construction materials available locally; finances available to install and maintain the system; and the priorities (based on sustainability criteria) of the intended biogas user [4]. These factors make up the inputs to the model, enabling a holistic first assessment of biogas technology designs that are available and suitable for a wide range of applications in SSA. The OBSDM has been developed in Microsoft Excel using Visual Basic for Application (VBA) programming. User inputs are minimised through the use of internal databases on different biogas technologies, feedstocks, country-specific climate data, construction materials, which can be updated or altered as required by the user. The model was applied to a typical rural household in Kenya and the Adamawa region of Cameroon, based on survey data with the results presented in section 3.1.

1.1 Principles of biogas technology in the SSA context

Biogas technology harnesses the anaerobic digestion (AD) process in one or more digester tanks to convert organic waste into energy in the form of biogas, and digestate that can be applied as fertiliser. Biogas is a mixture of 50-70% methane and 30-45% carbon dioxide, which can be utilised for cooking, lighting, heating, electricity generation, or upgraded to become a transport fuel [12, 13]. In SSA, the majority of biodigesters are household-scale systems where the biogas is used for cooking and (gas) lighting, as well as institutional scale for waste management and cooking [11, 14, 15]. The main feedstock used for household biodigesters is cattle dung, while institutional biodigesters use domestic sewerage and/or cattle dung [16-18]. However, there is also significant potential for energy generation from crop residues and the organic fraction of municipal solid waste (OFMSW), as well as wastes from agro-processing and food production industries for commercial biodigesters [4]. The application of commercial biodigesters in SSA is still very limited with unique examples in Ghana, Kenya, Nigeria, South Africa and Uganda [19-25].

Biogas technology is appealing in SSA due to its ability to help improve energy access, waste management, sanitation, and the indoor cooking environment [6, 26-28]. In addition, the technology is scalable and possible to construct systems from local materials [29-31]. Biodigesters have been installed in SSA since the 1950s, although in low numbers and varying degrees of success [32, 33]. In recent years, the 'Biogas for Better Life Initiative' was launched in 2007 with hopes to create a commercial domestic biogas market throughout the African continent [3]. From this initiative, the African Biogas Partnership Program was established, which supports domestic biogas programmes in five SSA countries; Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso [34]. Domestic biodigesters can help improve livelihoods and reduce the strain on the environment through replacing traditional open fire stoves with smokeless biogas stoves. Use of traditional stoves in homes leads to a build-up of thick smoke, particulates and hazardous pollutants such as carbon monoxide, sulphur and nitrogen oxides, due to a lack of flue or ventilation [10, 35]. The uncontrolled use of wood fuels and other traditional biomass resources is causing environmental problems including land degradation in drylands, destruction of forests, aggravated soil erosion, and flooding in SSA [36-38]. These environmental concerns are considerable in SSA given that over 90% of the population use wood fuels as an energy source, predominately for cooking [36]. Increasing awareness about biogas technology and its benefits in SSA along with designing biogas systems to suit the specific context and priorities of the intended users is an important part of improving the uptake of the technology in the region [4, 7]. The OBSDM was developed with this in mind.

2 Developing an optimal biogas system design model

2.1 Factors to consider in the design of biogas systems

Biogas system design requires consideration of the following, four interacting factors: the energy demand; the amount and nature of the feedstock available; the economics of the system; and the location where the system is to be installed, with consideration of the climate, soil conditions, land area available for installation, and water supply [39]. In SSA, 40% of the population live in water scarce environments, making water availability a crucial factor in biogas system design [40]. The OBSDM has been designed with these interacting factors forming four of the five main input sections. The fifth input section relates to the priorities of the user, and forms the criteria on which the optimal design is identified. Existing decision making tools for biogas technology focus largely on the financial viability of installing systems, and require detailed information on the installation and operational costs, or only provide the cost of one particular type of system (often suitable only for farms).

Karellas et al. [41] developed an Investment Decision Tool (IDT), which calculates the economic performance of a biogas plant in terms of internal rate of return (IRR), net present value (NPV), and simple payback period. The IDT is applicable to European commercial biogas systems, ranging from 50 to 5000 m^3 in size, which use agricultural waste and energy crops as feedstock to generate electricity and compost to sell [41]. Other online calculators and biogas feedstock databases exist in the European context, particularly Germany, which can be used to estimate the economic potential of commercial and farm-scale projects [42-44]. In the United States, a range of online tools for estimating energy production potentials from different biogas feedstocks are available, including the Iowa Biogas Assessment Model (IBAM) [45-47]. IBAM is an economic analysis tool for potential biogas projects based on feedstock sources available in the state of Iowa in the USA. The IBAM uses the combination of an online calculation spreadsheet and a geographical information system (GIS) to provide an economic analysis for potential biogas projects based on the feedstocks selected and identified via an online map of the state of Iowa [48].

For developing countries, the biogas calculation tool from the Alternative Energy Promotion Centre (AEPC) in Nepal stands as a unique example [49]. The AEPC biogas calculation tool is presented as a Microsoft Excel spreadsheet that can be used to help plant designers conduct technical and financial assessments for biogas projects in Nepal [49]. A number of details have to be entered into the biogas tool by the plant designer including details on the biogas plant type, installation and operation and maintenance (O&M) costs of the biogas plant, along with feedstock supply and the application of the generated gas. The tool is intended for larger scale systems – institutional, community, commercial, or waste to energy – where most design parameters are already chosen. In contrast to these existing tools and models, the OBSDM is intended to provide a holistic first assessment of the biogas technologies available for a wide range of applications specific to the SSA context including household, community, and industrial scale plants. It can be used by NGOs, government entities and other stakeholders in the SSA biogas industry as a first assessment of which type of biogas technologies are suitable for different applications. User inputs are minimised through the use of internal databases on different biogas technologies, feedstocks, country-specific climate data, construction materials, which can be updated or altered as required. To assist with calculating costs, the model is linked to an online currency exchange rate database.

2.1.1 Energy demand

The intended purpose of the biogas system is defined in the energy demand section of the OBSDM. As recommended by Werner et al. [50], estimating the energy demand of the intended user is the ideal starting point when advising on biogas installations. The user can choose one or more application options including cooking gas, lighting, electricity, and waste management. Lighting has been listed as a separate energy option than electricity, as biogas lamps are commonly used in domestic biogas systems, which are not as efficient as electric light globes, but provides a low cost option relative to kerosene lamps [51]. Waste management will be a function of a biogas system if organic waste is used as feedstock. Regardless of whether it is used exclusively for this purpose or for energy production, listing all types of uses for the system in the SSA context enables the user to become aware of all the possible functions of the system and choose the most relevant to their situation. The user is required to specify the number of units and hours of each particular energy application required, specifically the number of cooking stoves, number of lamps, and any electrical loads (including power rating of appliances in W and time of use). Based on this user information, the total daily volume of biogas required in m^3 and the total daily energy (in kWh/d) are estimated using the biogas and power consumption rates (total power consumed by the appliance) given in Table 1.

Table 1: Estimated biogas and power consumption of household energy applications

Appliance type	Biogas consumption (L/h)	Power consumption (kW)	Reference
Household burner (cookstove)	461*	3.35*	[52-54]
Gas lamp, equivalent to 60W bulb	161*	0.06	[50, 52, 53]
1 kWh electricity generation in biogas/diesel engine with 22.9%* efficiency	988.4*	4.37	[52, 53, 55-57]

*Average of values from references

In addition to entering details regarding the intended energy requirements of the biogas system, the user is also required to enter details about their current energy use to enable comparisons to be made of the potential biogas system and current energy sources. The user is required to select the type of energy used for cooking, lighting, and electricity from a drop-down menu and enter the amount, cost, and preparation time (h) required for each type. This information is used to estimate the annual energy costs, hours spent preparing current energy sources, GHG emissions (in t CO_2 equivalent/a), and the annual energy consumption (kWh/a). The costs per kWh are also estimated. The calorific values of each of the fuel types and the mass of CO_2 equivalent GHG emissions per kWh of delivered energy are used in the model to calculate the annual energy consumption and GHG emissions, respectively (Table 2).

Table 2: Calorific values and CO_2 equivalent GHG emissions per kWh of delivered energy for conventional fuels in SSA

Fuel type	Calorific value (kWh/kg)	CO_2-e GHG emissions (g/kWh delivered energy)	Reference
Charcoal	8.31	2147	[17, 58-60]
Charcoal (improved stove)	8.31	1706	[17, 58-60]
Coal	8.74	2753	[58, 61-63]
Crop residues	4.78[a]	4144	[64, 65]
Firewood	3.81[a,b]	4379	[17, 60-63]
Firewood (improved stove)	3.81[a,b]	2554	[17, 59, 60, 62, 63]
Dung	2.44	4381	[61, 66]
LPG	12.78[a]	513	[58, 61, 67]
Kerosene	12.17	638	[65, 68]
Electricity grid	1.00	293	[69]
Diesel	12.00	1700	[58, 70]

[a] Average of values from references

[b] Average of air dried and fresh wood with moisture contents of 15% to 20% and 50%, respectively

2.1.2 Feedstock

The type of feedstock used in a biogas system is the most influential parameter as it determines the amount of biogas that can be produced, the type of biogas technology that can be used, and the system operation [28]. All the organic components required for the AD process are provided by the feedstock [12, 28]. Organic substrates suitable for AD have a high biodegradability, such as fats, sugars, proteins, and starch based compounds, and examples of less ideal substrates include hemicellulose, cellulose, and lignin organic substances with a lower biodegradability [12, 28]. Key feedstock parameters, which influence biodegradability are: total solids (TS) or dry matter content (DM), volatile solids (VS) or organic dry matter content (oDM), biogas yield and methane content (or methane yield), and the rate and reliability of supply [71, 72]. In SSA, cattle manure is the main feedstock used in biogas systems, however, there is potential to use a wide range of organic wastes [5]. Using a combination of feedstocks, known as co-digestion, such as the organic fraction of municipal solid waste (OFMSW) and sewage sludge or crop residues and animal manure, can provide the right balance of nutrients and increase the methane yield [73-75]. The user is able to model using up to 8 different feedstocks in the OBSDM from a total of 40 feedstocks under the categories of cattle manure; livestock food product waste; other manure and sewage; vegetable and food waste; roots, tuber, and market waste; fruit and nut waste; crop residues, and; straw and grass (some of which are presented in Table 3). For each feedstock selected, the amount, rate of supply (e.g. daily), time taken to collect, and the distance from the proposed installation site of the biogas system needs to be entered. A biogas system is considered to be very feasible if the feedstock is within 3 km of the installation site [76]. The maximum daily biogas production potential (*BPP*) is calculated in the model as outlined in the following equation:

$$BPP\ (m^3/d) = \sum 1/2\left[(m_i\ (kg/d) \times DM_i \times oDM_i \times BY_i(m^3/kg\ oDM)\right. \\ \left. + \left(m_i\ (kg/d) \times BY_{FM,i}(m^3\ /t\ FM)/1000\right)\right] \quad (1)$$

Where m_i is the daily mass input of each chosen feedstock type and BY_i and $BY_{FM,i}$ are the corresponding biogas yields per kg of oDM and t of fresh matter (FM), respectively, from the database. The average of the two different methods of calculating biogas production potential is used to derive a more accurate estimate of the maximum daily biogas potential from the selected feedstocks. The daily energy production potential (*EPP*) is then calculated as given in the expression below:

$$EPP(kWh/d) = \sum BPP_i(m^3/d) \times EY_i(kWh/m^3) \quad (2)$$

Where EY_i is the energy yield in kWh per m^3 of biogas produced for each chosen feedstock type from the database. These BPP and EPP values are used to determine whether the feedstock supply is sufficient to meet all the energy needs, providing an alert to the model user if the supply is insufficient. BPP and EPP present the biogas and energy production under ideal conditions, in practice the actual biogas and energy production will be lower. The calculations for adjusted BPP and EPP figures based on methane yields according to digester operating temperatures and digester size are presented in section 2.2.

Table 3: Excerpt of feedstock database in OBSDM

Feedstock Category	**Feedstock**	**DM (%)**	**oDM (% of DM)**	**Biogas yield (m^3/kg oDM)**	**CH_4 content by vol. (%)**	**Biogas yield (m^3/t FM)**	**Energy yield (kWh/ m^3 biogas)**	**C:N ratio**	**Min recomm. RT (d)**	**Max recomm. RT (d)**	**Ref.**
Cattle manure	Cattle (dairy) manure	11%	62%	0.35*	53%*	52*	5.50*	20*	40*	75*	[77]

Feedstock Category	Feedstock	DM (%)	oDM (% of DM)	Biogas yield (m^3/kg oDM)	CH_4 content by vol. (%)	Biogas yield (m^3/t FM)	Energy yield (kWh/ m^3 biogas)	C:N ratio	Min recomm. RT (d)	Max recomm. RT (d)	Ref.
	Cattle dung	18%	85%	0.38	61%	52	6.28	19	40	75	[50, 78-83]
Livestock food product waste	Eggs	25%	92%	0.975	60%	-	6.22	5*	3*	30*	[12]
	Milk (whole)	8%	92%	0.9	60%	-	6.22	5.9	3	10	[12]
Other manure & sewage	Poultry manure (with straw)	70%	85%	0.38	56%	230	5.80	12	30	80*	[50, 78, 82]
	Night soil (pit toilet waste)	18%	84%	0.24	66%	37	6.79	8	70	100	[18, 27, 71, 82, 84, 85]
	Pig manure	20%	85%	0.31	63%	57	6.53	15	50	55	[50, 78, 82, 86]
	Sheep/goat manure	25%	80%	0.45	55%	108	5.70	18	50*	60*	[78, 82]
Vegetable & food waste	Vegetable waste	15%	76%	0.5	56%	57	5.80	15	10	40	[43, 87, 88]
	Kitchen/food waste	23%	90%	0.318	54%	-	5.63	17*	10	40	[87-89]
	Organic fraction MSW	31%	85%	0.406	72%	130	7.43	18	15	50*	[71, 90-92]
Roots, tuber & market waste	Market waste	22%	77%	0.520	64%	42.7	6.63	25	10	40	[12, 78, 87-89, 93]
	Root consumables/ residues	17%	87%	0.649	52%	95.9	5.37	25*	10	40	[43, 87, 88]
Fruit & nut waste	Spent fruits	35%	93%	0.55	60%	-	6.22	40	8	40	[12, 87, 88]
	Groundnuts, shelled (bruised)	89%	94%	0.663	63%	549	6.50	35*	10	40	[43, 87, 88]
Crops & residues	Millet/ sorghum	21%	92%	0.563	51%	107.2	5.28	63	10	40	[43, 87, 88]
	Cassava pulp	31%	98%	0.573	60%	-	6.25	100*	10	40	[86, 88]
	Water hyacinth	7%	N/A	0.25	60%*	-	6.22	25	10	40	[54]
Straw & grass	Young grass	50%	58%*	0.415*	60%	-	6.22	12	10	40	[82, 87, 88]
	Maize straw	86%	72%	0.7	45%	-	4.70	52	10	40	[12, 50]
	Rice straw	59%	83%	0.585	60%	-	6.22	75	10	40	[12, 82]

* Estimate

2.1.3 Location

The location where the biogas system is to be installed is another critical factor in the design of a biogas system. Location influences the heating and water requirements along with the type of construction and materials available. The amount of water and type of feedstock available at the site determines the possible range of total solids (TS) of the input stream into the biogas system. Different biogas technologies operate under different TS ranges, for example fixed dome digesters commonly used in SSA operate at a TS between 6% and 10% [18]. Fresh water requirements can be reduced or eliminated by using cattle urine, grey water, or connecting a toilet to the biogas system [5]. A distance of 1 km is considered as the maximum distance a person should walk in order to get water for a domestic biogas system to ensure that water access is not a limiting factor in the technology's uptake when water reticulation is unavailable [5]. In the OBSDM, the user is required to include the amount of water available in litres per day, the time required to collect it, as well as the average annual rainfall. The possible TS range based on the feedstock and water supply is determined as follows:

$$\begin{gathered} TS_{in-min} = \left(\sum DM_i \times m_i\right) / \left(\sum m_i + m_w\right) \\ TS_{in-max} = \sum DM_i \times m_i / \sum m_i \end{gathered} \qquad (3)$$

Where $TS_{in\text{-}min}$ is the minimum TS based on the input feedstock mix and daily amount of water available, m_w, and $TS_{in\text{-}max}$ is the maximum TS based on the average DM of the feedstock mix.

The operating temperature of the system and potential heating requirements are identified in the model based on the climatic conditions at the site. Climatic data, specifically mean daily temperature, mean daily high temperature, mean daily low temperature, and maximum temperature between day and night, can be entered by the user or, alternatively, country averages from the internal database are used. The operating temperature of a biogas system is important as it influences the rate of the microbial activity in the digester [94]. Methanogenic bacteria are particularly sensitive to fluctuations in temperature, which can inhibit biogas production [28, 95]. Heating requirements are determined as given in the expression below:

$$Heating\ required \begin{cases} T_{dig-op} = P, & (T_{a-max} - T_{a-min})/12 \geq 2 \\ T_{dig-op} = M, & (T_{a-max} - T_{a-min})/12 \geq 1 \\ T_{dig-op} = T & \\ \quad T_a \leq T_{op-min} & \end{cases} \qquad (4)$$

Where $T_{dig\text{-}op}$ is the digester operating temperature range, which can be psychrophilic (<20°C), P; mesophilic (35-42°C), M; or thermophilic (50-60°C), T [5, 12, 96, 97]. T_a, $T_{a\text{-}max}$ and $T_{a\text{-}min}$ denote the mean daily ambient temperature, mean ambient high temperature, and mean ambient low temperature, respectively. The limits indicate the hourly temperature fluctuations based on an average 12-hour period between $T_{a\text{-}max}$ and $T_{a\text{-}min}$. $T_{\text{op-min}}$ is the minimum outside temperature in which the biodigester can operate. This differs from the digester operating temperature range, e.g. underground fixed dome biodigesters can operate in the mesophilic operating range with outside temperatures ranging between 10°C to 40°C [76].

Heating requirements for biogas systems can be minimised through the use of insulation, which in part consists of underground installation in developing regions. To determine if underground construction is feasible, the shallowest groundwater depth at the installation site at any point throughout the year needs to be entered in the model along with the soil type, selected from the list of 15 soil types found in SSA (Table 4). Underground construction is considered feasible in the OBSDM if the soil type is suitable for underground construction for specific digester designs, and the maximum excavation depth required for the biogas system installation is less than the shallowest groundwater depth. The final user inputs in the location section are the amount of fertiliser required per year, the cost of the fertiliser, the area available for installing the system, and the local construction materials (selected from a list) and their respective costs (either default country average costs or user-defined local costs).

Table 4: Soil types database in OBSDM based on [98, 99]

Soil type	Code	Definition
Arenosols	AR	Loose, sandy soil
Calcisols, Cambisols, Luvisols	CL	Limestone, sandy loam or high base clay soil
Gypsisols, Calcisols	GY	Soil with gypsum and/or limestone
Acrisols, Alisols, Plithosols	AC	Low base/highly acid soil susceptible to water erosion, clay-rich with/without iron minerals, may contain aluminium
Andosols	AN	Volcanic soils, high aluminium content, excellent water & nutrient holding capacity
Fluvisols, Gleysols, Cambisols	FL	Marsh or wetland soil with/without sandy loam
Ferralsols, Acrisols, Nitisols	FR	red/yellow soil with metal oxides (incl. tropical red soil), fine texture, may be clay rich
Gleysols, Hitosols, Fluvisols	GL	Wetland/swamp/marsh soil
Leptosols	LP	Shallow soil over continuous rock with gravel/stone
Lixisols	LX	Soil with high clay content in subsoil, common in tropical regions with dry season/s, high erodibility
Nitsols, Andosols	NT	Red tropical soil with/without volcanic soil
Plantosols	PL	Light-coloured soil, clay in subsurface, seasonal waterlogging and drought stress
Pozdols, Hitosols	PZ	Ash-grey top layer of coarse texture, subsurface of humus and metal oxides (common in humid tropics & light forest regions) with/without wetland soil
Solonchaks, Solonetz	SC	Soil high in soluble salts, common in arid/semi-arid/coastal regions may have dense subsurface with high clay content
Vertisol (black cotton soil)	VR	Heavy textured soil, high in expansive clay, unstable -shrinking and swelling

2.1.4 Economics and priorities of the user

The final input sections of the model are used to assist in identifying which type of biogas technologies are most suitable based on the intended user's economic situation and priorities. Economic inputs include monthly disposable income, savings available for capital expenditure, and details on any government subsidies that may be available for biogas technology. The high installation costs of biogas systems in SSA currently presents a significant barrier to increased uptake of the technology [7]. As such, the OBSDM includes low cost biogas systems in the digester database. The priorities listed in the user inputs were chosen based on technical, economic, environmental, and social sustainability criteria related to biogas systems. The users can rate each priority criteria from a scale of 1 to 5 with 1 being not at all important and 5 being extremely important (Table 5).

Table 5: Priority criteria and associated parameters and source in OBSDM

Priority Criteria	Parameters	Source
Reliability	• Lifespan of digester • Gas pressure variability (constant or varying)	• Biodigester database
Robustness	• Sensitivity to changes in ambient temperature • Vulnerabilities to structural integrity of biogas system	• User input – local climatic conditions/internal climate database for SSA countries • Biodigester database
Simple operation & construction	• Daily operation time (h) • Annual maintenance required (h) • Level of expertise required for operation • Construction time (d)	• Biodigester database
Low cost	• Installation costs (including and excluding subsidies) • Operation & maintenance (O&M) costs • Annual savings • Net present value (NPV) • Simple payback period (y) • Affordability (monthly disposable income - monthly O&M costs) • Additional savings required to meet capital costs • Months of savings required to meet capital costs	• Biodigester database • User input – energy demand (current fuel source costs), location (fertiliser & local construction material costs) & economics • Construction materials database
Technical efficiency	• Biogas production efficiency (%) • Proportion of energy requirements met (%) • Specific gas production per digester volume (m^3 biogas/m^3 installed)	• User input -energy demand, feedstock • Biodigester database
Environmentally benign	• GHG emissions avoided from waste management (t CO_2-e/y) • GHG emissions avoided from fuel replacement (t CO_2-e/y) • GHG emissions from construction (t CO_2-e/y) • Energy returned on energy invested (EROI)	• User input – energy demand, feedstock • Construction materials database • Biodigester database
Local materials & labour	• Employment generation (unskilled/skilled ratio for installation) • Proportion of required construction materials available locally (%)	• Biodigester database • User input – location (local construction materials)
Save time	• Time saved from replacing current energy demand (h/d) • Time required to operate & maintain the system (including feedstock and water collection) (h/d)	• User energy input – energy demand (current fuel sources), feedstock, location (water supply) • Biodigester database

2.2 Biodigester sizing and selection

Biogas systems are sized according to the volumes required for the digester, containing the water and feedstock mix where the AD process occurs, and the gasholder storing the produced biogas temporarily prior to its application for energy production. The key influencing factors to digester sizing are hydraulic retention time (HRT), organic loading rate (OLR), and temperature. The volume of a digester may be determined based on either the HRT or OLR; and the chosen digester volume will then determine the other, as given in the following equations:

$$HRT(d) = \frac{V_{dig}(m^3)}{\dot{V}(m^3/d)} \qquad (5)\ [28]$$

$$OLR(kg\ oDM/(m^3/d)) = [m\ (kg/d) \times DM \times oDM]/V_{dig}\ (m^3) \qquad (6)$$

Suitable sizes for biodigesters can be determined based on maximising biogas production, maintaining process stability, and minimising system energy requirements and process costs, the combination of these requiring trade-offs as not all factors can be maximised simultaneously [100]. Higher OLRs require longer HRTs which increases the required digester size and cost, but also the methane production [101]. A theoretical HRT range is defined in the OBSDM according to the recommended digester and feedstock ranges as follows:

$$\begin{aligned} HRT_{th\_min}(d) &= \max(HRT_{dig\_min}, HRT_{FS\_min}) \\ HRT_{th\_max}(d) &= \min(HRT_{dig\_max}, HRT_{FS\_max}) \end{aligned} \qquad (7)$$

Where HRT_{dig_min} and HRT_{dig_max} are the minimum and maximum HRTs of a given digester in the model's digester database. HRT_{FS_min} and HRT_{FS_max} are the minimum and maximum recommended HRTs of the feedstock, as given in Table 3. Where a combination of feedstocks is used, HRT_{min} and HRT_{max} are determined by calculating the sum-product of the minimum and maximum HRT of each feedstock type relative to the mass of each feedstock and total mass, respectively. The HRT ranges are used to derive a suitable digester volume range, V_{dig_min} and V_{dig_max} for each digester type in the model:

$$\begin{aligned} V_{dig\_min}(m^3) &= \left[\left(\sum m_i + m_{w\_min}\right)(kg/d)/1000(kg/m^3)\right](m^3/d) \times HRT_{min}(d) \\ V_{dig\_max}(m^3) &= \left[\left(\sum m_i + m_{w\_max}\right)(kg/d)/1000(kg/m^3)\right](m^3/d) \times HRT_{max}(d) \end{aligned} \qquad (8)$$

Where m_{w_min} and m_{w_max} are the minimum and maximum amounts of water required to be added to the digester with the feedstock each day. The water input requirements are determined based on the maximum and minimum total solids content at which a digester can function properly, TS_{dig_max} and TS_{dig_min}, respectively, as well as the dry matter content and volume of each feedstock with the density of the feedstock and the input mix being approximated to the density of water, as in the following equation:

$$\begin{aligned} m_{w\_min}(kg/d) &= \begin{cases} 0, & TS_{in-max} < TS_{dig\_max} \\ \left(\sum DM_i \times m_i\right)/TS_{dig\_max} - \sum m_i & \end{cases} \\ m_{w\_max}(kg/d) &= \left(\sum DM_i \times m_i\right)/TS_{dig\_min} - \sum m_i \end{aligned} \qquad (9)$$

The amounts of water required for each biodigester type are also used to identify the feasible types using the following conditions:

$$feasible\ biodigester\ type \begin{cases} TS_{in\_min} < TS_{dig\_max} \\ TS_{in\_max} > TS_{dig\_min} \\ OR(m_{w\_min} < m_w, m_{w\_max} \leq m_w) \end{cases} \quad (10)$$

Where a biodigester type is considered feasible provided these conditions are true.

The derived digester volume and HRT ranges of the feasible biodigester types are used to determine the resulting maximum and minimum OLR, using Equation (6):

$$\begin{aligned} OLR_{max} &= \left[\sum(m_i \times DM_i \times oDM_i)\right]/V_{dig\_min} \\ OLR_{min} &= \left[\sum(m_i \times DM_i \times oDM_i)\right]/V_{dig\_max} \end{aligned} \quad (11)$$

The derived OLR range is applicable to digesters operating in the digester temperature for which the HRT range was assigned, T_{HRT}, however, the actual digester operating temperature, T_{dig}, may differ from this depending on the climatic conditions and the digester type. At lower temperatures, for example, a lower OLR and higher HRT is required to achieve comparable biogas production rates. To determine the adjusted OLR range, $OLR_{max,adj}$ and $OLR_{min,adj}$, the following equation is applied [102]:

$$\begin{aligned} OLR_{max,adj} &= e^{p(T_{dig}-T_{HRT})} \times OLR_{max} \\ OLR_{min,adj} &= e^{p(T_{dig}-T_{HRT})} \times OLR_{min} \end{aligned} \quad (12)$$

Where p is the rate constant (1/°C), which is 0.10 for the temperature range of 10°C to 30°C [102]. T_{dig} is estimated to be the average of T_a and $T_{a\text{-}max}$ for unheated underground or insulated systems and equivalent to T_a for unheated above ground systems, otherwise the digester temperature is equal to the set temperature of the heating system, T_{set}:

$$T_{dig} = \begin{cases} T_a, & above\ ground, no\ insulation \\ (T_a, T_{a-max})/2, & undergound\ const./insulation \\ T_{set}, & heated\ digester \end{cases} \quad (13)$$

T_{HRT} is estimated in the same manner, unless specified, based on the average ambient temperature of the country where the system is available.

The adjusted OLR range is then used to recalculate the digester volume range, $V_{dig\_min,adj}$ and $V_{dig\_max,adj}$, and the resulting HRT range. The ideal digester volume recommended by the OBSDM for each biodigester type is the mean volume of the digester volume range as this provides a compromise between minimising costs ($V_{dig\_min,adj}$), and maximising biogas production and process stability ($V_{dig\_max,adj}$):

$$V_{dig\_ideal} = (V_{dig\_max,\mathrm{adj}} + V_{dig\_min,\mathrm{adj}})/2 \quad (14)$$

Once a recommended digester size has been determined for each feasible biodigester type, the model compares each available digester size, V_{dig_avail}, to V_{dig_ideal}, and identifies the feasible digester volumes, $V_{dig\_avail\_feas}$, according to the equation given below:

$$V_{dig\_avail\_feas} = \begin{cases} \left\| V_{dig\_ideal}/V_{dig\_avail} \right\| \times V_{dig\_avail}, & V_{dig\_ideal}/V_{dig\_avail} \geq 0.5 \\ V_{dig\_avail}, & 0.5 < V_{dig\_ideal}/V_{dig\_avail} \geq 0.15 \\ 0 & \end{cases} \quad (15)$$

Where the nearest integer is used to determine the multiples of V_{dig_avail} required if V_{dig_ideal} is half of the available size or larger in volume. If the ratio of V_{dig_ideal} to V_{dig_avail} is less than half and greater than 0.15, V_{dig_avail} is chosen as the feasible digester size. A ratio less than 0.15 indicates that V_{dig_avail} is significantly larger than the ideal digester volume and therefore the available digester size is not considered feasible. The 0.15 boundary is derived from it being the minimum ratio value that allows at least the smallest available size of each biogas system type in the OBSDM to be considered based on a feedstock supply of cattle dung from 1 cow (12.25 kg/d [82, 103]).

Equations (16) to (18) are used to calculated the average HRT, HRT_{avg}, number of digesters, n_{dig}, and percentage change from the ideal volume.

$$\begin{gathered} HRT_{min}(d) = V_{dig\_avail\_feas}(m^3)/\left(\sum m_i + m_{w\_max}\right)(kg/d)/1000(kg/m^3) \\ HRT_{max}(d) = V_{dig\_avail\_feas}(m^3)/\left(\sum m_i + m_{w\_min}\right)(kg/d)/1000(kg/m^3) \\ HRT_{avg}(d) = (HRT_{min}(d) + HRT_{max}(d))/2 \end{gathered} \quad (16)$$

$$n_{dig} = V_{dig\_avail\_feas}/V_{dig\_avail} \quad (17)$$

$$\%\ change = \left(V_{dig\_avail\_feas} - V_{dig\_ideal}\right)/V_{dig\_ideal} \times 100 \quad (18)$$

The installation costs of each feasible digester size (excluding any subsidies that may be available), are estimated based on the average of the recommended retail price (RRP) (where available), and the total costs of the required construction materials, considering the cost of value-added tax (VAT), if applicable. These costs along with HRT_{avg}, n_{dig}, and *% change* are sizing parameters used to identify the optimal feasible digester size for each biodigester type through applying the technique for order preference by similarity to ideal solution (TOPSIS) method with details provided in section 2.3.

The associated gasholder size based on the selected digester size becomes the selected gasholder volume. Kossmann et al. [29] recommend that the gasholder is sized to cover the peak gas consumption rate and the gas storage required during the longest zero-consumption period. This method is applied and compared to the available gasholder volume to determine whether additional gas storage is required. The peak gas consumption rate is the daily required gas consumption based on the energy demand input. The maximum zero-consumption period is estimated to be 10 hours in a day. The daily methane production potential (*MPP*) is estimated using the kinetic model for steady state methane production rates from Chen and Hashimoto [101, 104, 105] as given below:

$$\begin{aligned} MPP\ (m^3/d) = {} & [(m_i\ (kg/d) \times DM_i \times oDM_i \times BMY_i (m^3 CH_4/kg\ oDM) \\ & \times (1/1000)(kg/m^3)][1 - K/(HRT \times \mu_m - 1 + K)] \end{aligned} \tag{19}$$

Where BMY_i is the methane yield for a chosen feedstock per kg of oDM, and K is the relative substrate micro-organism binding constant, which can be determined based on the equations given below for cattle manure and swine manure, respectively [104, 105]:

$$K = 0.8 + 0.0016 e^{0.06(m_{oDM}/m \times 1000)} \tag{20}$$

$$K = 0.6 + 0.0206 e^{0.051(m_{oDM}/m \times 1000)} \tag{21}$$

For all other feedstocks types the K value for swine manure is used, which was also used by Abarghaz et al. [106] for a mixture of feedstocks. The maximum specific growth rate, μ_m, is affected by temperatures over the range of 20°C to 60°C as follows [104]:

$$\mu_m = 0.013 T_{dig} - 0.129 \tag{22}$$

The required gasholder volume, V_{gh} with an added safety factor of 15%, therefore can be calculated based on the estimated daily biogas consumption (equivalent to the energy demand), V_{cons}, and the maximum period of zero gas consumption (10 hours per day), where f_{CH4} is the fraction of methane in biogas, and η_{BP} is the biogas production efficiency for a given biodigester type:

$$V_{gh}(m^3) = \begin{cases} 1.15 \times \max\left[V_{cons}, 10/24 \times \left(MPP/\bar{f}_{CH_4}\right) \times \eta_{BP}\right], V_{cons} \leq \left(MPP/\bar{f}_{CH_4}\right) \times \eta_{BP} \\ 1.15 \times 10/24 \times \left(MPP/\bar{f}_{CH_4}\right) \times \eta_{BP} \end{cases} \tag{23}$$

Additional required gas storage volume is calculated as the difference between the required and available gasholder volume. *MPP* is used to calculate the required gasholder volume rather than

BPP, which is based on the biogas production potential under ideal conditions and does not enable the variation in methane production according to digester temperature to be considered.

2.3 Determining the optimal design using Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA), specifically the TOPSIS approach, is used to identify the optimal biogas system design. In the TOPSIS method, each design option is ranked according to its distance from the ideal solution, with the best option being identified as having the shortest weighted distance from the ideal solution and the longest distance from the worst [107]. This method is used to find the optimal size for each feasible biodigester type as well as identifying the most suitable overall biogas system design. The biogas digester types that are technically feasible are identified based on the user inputs related to feedstock and location as discussed in sections 2.1.2 to 2.1.3. To help determine the optimal size for each feasible biodigester type, vector normalisation (Equation (24)) is applied to each of the sizing parameters (described in section 2.2) for all possible digester volumes and the best and worst scores for each parameter are identified. The best score for HRT_{avg} and installation costs is the maximum normalised HRT_{avg} and installation cost scores (where costs are considered as negative values), while the worst score is the minimum normalised score. For n_{dig} and *% change*, the best scores are the minimum normalised scores and the worst are the maximum normalised scores. The distance from the best and worst score, d^+ and d^-, respectively, is then calculated as the square-root of the squared sum of the difference between each normalised sizing score and the best and worst scores. The overall score, *z*, for each sizing option is then determined by applying Equation (27) with the optimal size then being identified as the one with the highest overall score.

Once the optimal size has been chosen in the model for each feasible biodigester type, the different design options are then ranked and compared by applying the TOPSIS method again. The ideal design in the OBSDM is the one which has the best possible weighted score for each priority criteria, while the worst solution is the design with the worst possible weighted score for each priority criteria (Table 6). A normalised decision matrix of M alternatives and N criteria is formed in the model, with the score for each priority criteria, j, of an biogas system design option, i, being derived from normalising parameter values, x [108]:

$$\hat{x}_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1} \left(x_{ij}\right)^2} \tag{24}$$

Table 6: Equations to determine ideal and worst scores for priority criteria in the OBSDM

Priority criteria	Ideal score (s^+)	Worst score (s^-)
Reliability, robustness, low cost[a], technical efficiency, reducing GHG emissions, local materials & labour, save time	$s^+ = \max(w_{ij} \times \hat{x}_{ij})$	$s^- = \min(w_{ij} \times \hat{x}_{ij})$
Simple operation & construction[b]	$s^+ = \min(w_{ij} \times \hat{x}_{ij})$	$s^- = \max(w_{ij} \times \hat{x}_{ij})$

[a] All costs are considered as negative values and all profit is given as positive values in the OBSDM, as is common practice in accounting, resulting in an objective function of maximising profits and thereby minimising costs.

[b] The objective function is to minimise the time required for construction, operation and maintenance, as well as the level of expertise required to operate the system.

The distance from the ideal score, d^+, and the worst score, d^-, for each digester design option is determined by the square-root of the squared sum of the difference between the ideal and worst scores, respectively, from the weighted scores of each option [107]:

$$d(s^i)^+ = \sqrt{\left\{\sum_{j=1} \left|s^+ - w_{ij} \times \hat{x}_{ij}\right|^2\right\}} \tag{25}$$

$$d(s^i)^- = \sqrt{\left\{\sum_{j=1} \left|w_{ij} \times \hat{x}_{ij} - s^-\right|^2\right\}} \tag{26}$$

Where w_{ij} is the weight assigned to a normalised priority criteria score for a given design option. The overall weighted score, z, of each option is determined as follows [107]:

$$z(s^i) = d(s^i)^- / \left[d(s^i)^- + d(s^i)^+\right] \tag{27}$$

The optimal design option is identified as the option which has received the maximum overall score.

3 Applying the OBSDM for rural household biogas systems in Kenya and Cameroon

The concept of the OBSDM can be realised through applying existing data to the model. Average data on rural households in Kenya and Cameroon based on two surveys was applied to the model to identify the optimal biogas system design for rural households in Kenya and Cameroon [109, 110]. The survey from Kenya was carried out in January 2014 in six different counties to assess the quality of the services provided by the Kenyan National Domestic Biogas Programme (KENBIP), the socioeconomic impact of household biogas systems, and to determine a baseline for the fuel situation [109]. A total of 240 households were surveyed across the six counties of Kericho, Nakuru, Kiambu, Murang'a, Machakos, and Kajiado, which are representative of the Western, Eastern and Central regions of Kenya [109]. In Cameroon, a total of 18 households in the Adamawa region were interviewed and their household air quality monitored between April and May 2015 [110]. The aim of the study was to assess the impact of biogas systems on household energy, water, labour, and indoor air quality [110]. Average data on energy use, water supply, fertiliser use, and income for rural households with and without biodigesters from both studies were inputs to the OBSDM (Table 7).

Table 7: Inputs to the OBSDM for average rural Kenyan and Cameroonian households based on survey data [109, 111]

Input parameter	*Kenya*	*Cameroon (Adamawa region)*
Energy demand		
Cooking h/d (per stove)	4.5 (3 meals for 4-5 people)	4.5 (3 meals for 9-10 people)
No. of stoves	1	2
Daily volume of biogas required (m^3)	*2.10*	*4.2*

Daily energy required (kWh)	*13.4*	*26.8*
Current daily cooking fuel consumption	4.8 kg firewood[a]	10.5 kg firewood
Current lighting fuel used		
Monthly Energy costs	0	12,133.33 FCFA (20.62 USD)[h]
Time spent preparing current energy sources (min/d)	51	28
Greenhouse gas emissions per year (t CO_2-e/y)	*29*	*64*
Feedstock		
Amount & type	77 kg/d dairy cattle manure	66 kg/d cattle manure
Time required to collect & transport feedstock to biodigester (min/d)	1	12.25
Daily biogas production potential (m^3)	*2.92*	*3.58*
Daily energy production potential(kWh)	*16.07*	*22.5*
Location		
Amount of water available (L/d)	63.5[b]	63.0
Time required to collect water	60 min[b]	15 min
Mean daily temperature (°C)	20.8[c]	23.8[c]
Mean high temperature during the day (°C)	26.9[c]	28.8[c]
Mean temperature in the coldest month (°C)	16.1[c]	18.8[c]
Maximum temperature difference between day and night (°C)	10.8[c]	10.0[c]
Shallowest groundwater table depth at any point throughout the year (m)	3[d]	2[i]
Soil type	Nitsols, Andosols[e]	Ferralsols, Acrisols, Nitisols[j]
Area available to install biogas system (m^2)	30	30
Amount of dry fertiliser required per year (kg DM/y)	1,386[f]	140.3[k]
Cost of fertiliser per kg	40.80 KSh (0.40 USD)[f,g]	360 FCFA (0.61 USD)[g,k]
Construction materials available locally	Stone, bricks, dressed quarry stones, cement, lime, gravel, coarse sand, waterproof cement, welded square mesh (G8) –heavy gauge, steel rod/round bar (8 mm), binding wire	Stone, bricks, cement, lime, gravel, coarse sand, fine sand, water proof cement, chicken wire (1800 mm wide), steel rod/round bar (8 mm), steel rod (6 mm), binding wire, feeding mixer
Monthly disposable income	5,000 KSh (49.35 USD)[g]	941.67 FCFA (1.60 USD)[g,l]
Savings available for capital expenditure	30,000 KSh (296.10 USD)[g]	5,650 FCFA (9.60 USD)[g,l]
Subsidies available	None	5% installation cost

[a] Based on an estimated consumption of 1.2 kg/pp/d [17]

[b] Average from [112]

[c] OBSDM country database, climatic data from [113]

[d] Based on the shallowest groundwater levels encountered for the Baricho Aquifer in the coastal strip, which is shallower than the groundwater levels of major aquifers in Kenya [114]

[e] Soils found in several regions of Kenya **[115]**

[f] Based on cost of 2,480KSh and 1,600KSh per 50kg bag of diammonium phosphate (DAP) and calcium ammonium nitrate (CAN) fertilisers, respectively [116]

[g] Based on an exchange rate of 1 USD = 101.32 KSh (current July 2016)

[h] Based on an exchange rate of 1 USD = 588.44 FCFA (current July 2016)

[i] Based on shallowest depth to water below ground level in buffer zone for bauxite mining project in Adamawa region [117]

[j] Based on dominant soils in the ferralitic zone [118]

[k] Based on an average annual spending of 50,500 FCFA for chemical fertiliser by farmers in Mezam division and a cost of 18,000 FCFA per 50 kg bag [119]

[l] Based on annual savings of 11,300 FCFA in 'Njangis' of farmers in Mezam division [119, 120]

While there are notable differences in the Kenyan and Cameroonian studies, the conditions of the surveyed rural households are comparable. The dominant cooking method in both study regions is three-stone wood stoves, and the main feedstock available for biogas production is cattle manure. No cost has been assigned to firewood use for an average Kenyan rural household, as the study noted that over half of surveyed households collect rather than purchase firewood. In Cameroon, over half of the surveyed households spent between 600 and 5000 FCFA per week on firewood [110]. The cattle grazing practices in the two regions differ, influencing the availability and time associated with cattle dung collection to feed the biodigester. Cattle from the Kenyan households remain in one cattle holding area close to the house for most of the year while in Adamawa cattle are only kept in kraals (cattle holding area) close to homes overnight during the dry season and left to graze away from their homes during the wet season [109, 110].

The model inputs of area available for installing the biogas system and construction materials available locally were estimated based on the type of biogas systems developed through the domestic biogas programmes in Kenya and Cameroon. The KENBIP began in 2008 as part of the Africa Biogas Partnership Programme (ABPP) and has helped increase biogas dissemination, with over 10,000 biodigesters installed since the programme began [121]. The programme developed the KENBIM fixed dome model [122]. Biogas dissemination in Cameroon has been more localised with pilot domestic biogas projects in selected regions such as Adamawa, while a national domestic biogas programme is being developed by the Ministry of Water and Energy (MINEE) through partnerships with the Netherlands Development Organisation (SNV), Heifer International, and Programme de Développement Durable du Lac Tchad (PRODEBALT) [111, 119, 123]. SNV has facilitated the promotion and construction of fixed dome designs based on the Nepalese model GGC 2047 in Cameroon [111]. The OBSDM does not include this Cameroonian fixed dome model in the digester database; however, it does include the comparable Rwanda III model, which also is based on the GGC 2047 model. Government subsidies are no longer available for Kenyan households under the KENBIP, while for rural households in Adamawa subsidies of 5, 25, and 45 percent were trialled as part of a study conducted by SNV and the Development Economics Group from Wageningen University [124]. The minimum subsidy of 5 percent was included as an input to the model. Priority criteria were rated in the model based on the survey responses in Kenya on the reasons for installing the system for both case studies, as this information was not available from Cameroon. The primary reasons for installing biodigesters were to make cooking more convenient as well as save money and time [109].

3.1 Results and discussion: Optimal design for rural Kenyan and Cameroonian households

The OBSDM identified a 6 m^3 Modified CAMARTEC stabilised soil blocks (SSB) digester to be optimal based on the specified conditions for both Kenyan and Cameroonian rural households (Table 8). Estimates from the model on the biogas production, proportion of cooking needs met, and the time saved by applying these biogas systems are conservative compared to the two survey results. The volumes of the majority of household biodigesters in the Kenyan study region were 8 m^3, providing 3 hours of cooking for a double burner stove with no households reporting a shortage of gas [109]. Comparatively, the model estimated the biogas system to provide a total of 3.2 cooking hours for a single stove, meeting 71% of the cooking energy needs of an average rural household in Kenya. The lower biogas production estimates relative to the energy required given by the model may be due to the average amount of feedstock fed to the digesters being greater than what was entered in the model. The Kenyan survey report provided figures for the average amount of dairy cattle, other cattle, market pig, and breeding pig dung fed to the biodigester per day, however, it did not specify the average per household, therefore some households may be using a combination of animal dung to feed their biodigesters. Furthermore, the amount of biogas required based on the number of meals and number of people per household is high at a rate of 150 L/pp/meal [50]. For an average household in Adamawa, the biogas system is estimated to provide 3.1 h of cooking each day, saving 3.6 kg/d in firewood and meeting 34% of the daily cooking requirements. This was due to the larger household size compared to the Kenyan case study. Firewood savings estimates are conservative compared to the Cameroonian survey results of 5.5 kg/d. Households in Kenya and Adamawa are estimated to spend an additional 55 and 37 minutes, respectively, to operate and maintain their biogas system. This is within the range reported in the Cameroonian survey (2 to 59 minutes) and attributable to the additional time required to collect feedstock [110]. The time Kenyan households spend on collecting feedstock and operating the biogas system was not reported in the survey, however, households did indicate that less time was spent on cooking [109]. Reductions in cooking time have not been included in the model and could lead to overall time savings. The OBSDM estimated that all fertiliser requirements will be met by the biogas system for Cameroon and 85% of the amount required by Kenyan households. Estimated financial savings from replacement of chemical fertiliser with bioslurry were within 0.3% of the estimated savings from the Kenyan survey, a total of 26,773 KSh and 21,296 KSh for DAP and CAN fertiliser replacement, respectively [109]. Due to the limited literature on the performance of bioslurry compared to other organic and chemical fertilisers and its economic value, there is no standard method of estimating the savings associated with fertiliser replacement [125]. However, experience from domestic biogas programmes, such as in Tanzania and Vietnam, have shown that the utilisation of bioslurry can provide significant financial benefits to biogas system owners [125, 126]. Estimates of savings from bioslurry use in the OBSDM are not dependent on the type of biogas system applied and therefore the uncertainties in the associated economic value do not undermine the objective of the model. The installation costs of the recommended biogas system from the OBSDM are based on average construction material and labour costs in Kenya and SSA for the Kenyan and Cameroonian case studies, respectively, and would need to be revised based on local costs for more reliable cost estimates.

The optimal biogas system design identified by the OBSDM reflect the context of the intended users. For rural Kenyan households where there are fewer water supplies relative to feedstock supply and the time taken to collect water is high compared to Cameroon, the recommended system could be operated with no water due to the low TS content of the feedstock (dairy cattle manure has a lower TS range than cattle dung). Out of the 9 technically feasible biogas system designs for Kenyan rural households and the 6 feasible designs for households in Adamawa, the Modified CAMARTEC SSB digester was found to have the highest overall score and the best scores for low cost and environmentally benign (Figure 1). The Modified CAMARTEC SSB digesters use interlocking stabilised soil blocks which are a cheaper and less energy intensive alternative to burned bricks commonly used in masonry fixed dome systems. The AGAMA BiogasPro, KENBIM, and PUXIN (Bioeco Sarl) designs were not feasible as the depth required for underground construction of these digesters was deeper than the minimum groundwater level. In both the Kenyan and Cameroonian household scenarios, the results indicate that masonry fixed dome systems, namely the KENBIM, all modified CAMARTEC digesters, and the Rwanda III system, are more cost effective than the remaining systems that are completely or partially prefabricated. The masonry fixed dome systems can be constructed from local materials, while the prefabricated systems have higher upfront costs. The flexi biogas digester was the only system which was found to be cost-competitive with the masonry fixed dome systems, however, its shorter lifespan results in higher costs per kWh. Descriptions of the technically feasible biogas system designs for both case studies as well as details on the comparison of priority criteria and associated sustainability parameters are provided in the Appendix with digester sizing details given in Table A.1, standardised scores given in Table A.2, and weighted scores given in Table A.3.

Table 8: Optimal biogas system design for rural Kenyan and Cameroonian households based on the OBSDM output

Digester design details	***Kenya***	***Cameroon (Adamawa region)***
Recommended digester	6 m^3 Modified CAMARTEC stabilised soil blocks digester	6 m^3 Modified CAMARTEC stabilised soil blocks digester
Recommended digester size	6.49 m³	5.27 m³
Available total digester size	6.00 m³	6.00 m³
Number of digesters	1.0	1.0
Total gasholder size	1.60 m³	1.60 m³
Additional recommended gas storage	0.00 m³	0.00 m³
Minimum amount of water required to mix with feedstock	0.0 L/d	39.0 L/d
Maximum amount of water required to mix with feedstock	63.5 L/d	63.0 L/d
Average hydraulic retention time (HRT)	62 d	49 d
Organic loading rate (OLR)	0.81 kg oDM/m³/d	1.8 kg oDM/m³/d
Estimated daily biogas production	1.48 m³	1.43 m³
Estimated daily energy production	8.2 kWh	9.0 kWh
Proportion of energy requirements met	71 %	34 %
Estimated daily cookstove hours	3.2 h	3.1 h
Estimated capital cost	69,265.71 KSh (683.98 USD)^{a}	369,277.51 FCFA (627.55 USD)^{c}
Estimated annual running costs	288.76 KSh (2.85 USD)^{a}	1,619.64 (2.75 USD)^{c}
Estimated simple payback period (years)	1.4	4.4
Estimated NPV	309,265.71KSh (3,052.37 USD)^{a,b}	173,112.80 FCFA (294.19 USD)^{b,c}
Annual savings	47,931.39 KSh (473.07 USD)	83,144.62 FCFA (141.30 USD)^{c}
Estimated time saved	-55.3 min/d	-36.8 min/d
Estimated greenhouse gas emissions reduced	24.2 t CO_2-e/y	25.7 t CO_2-e/y
Energy return on energy invested (EROI)	29.23	32.19
Estimated savings in firewood consumption	3.4 kg/d	3.6 kg/d

Digester design details	***Kenya***	***Cameroon (Adamawa region)***
Closest supplier contact details	Uganda Domestic Biogas Programme/SNV (the Netherlands Development Organisation)	Uganda Domestic Biogas Programme/ SNV (the Netherlands Development Organisation)

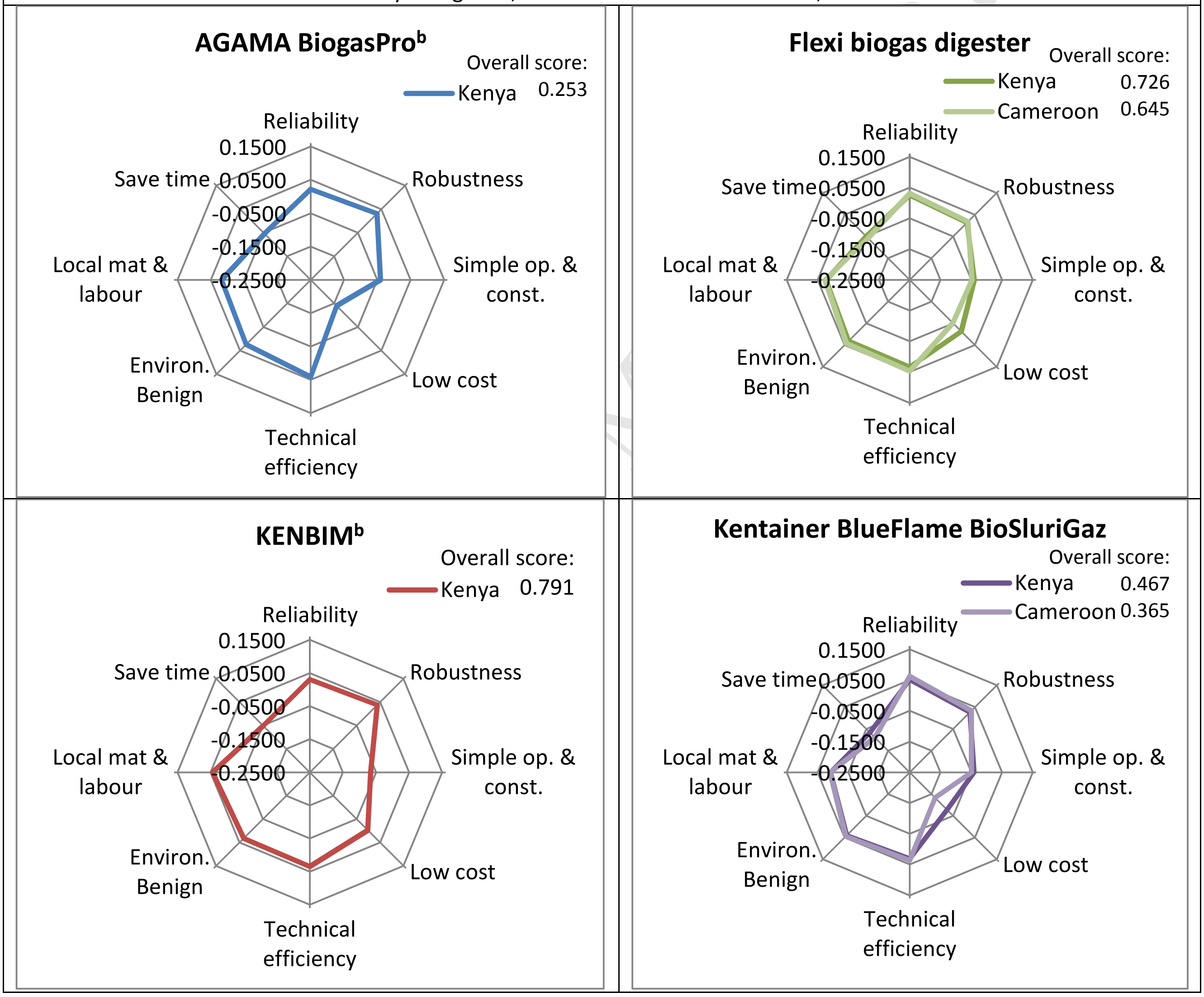
[a] Based on an exchange rate of 1 USD = 101.32 KSh (current July2016)

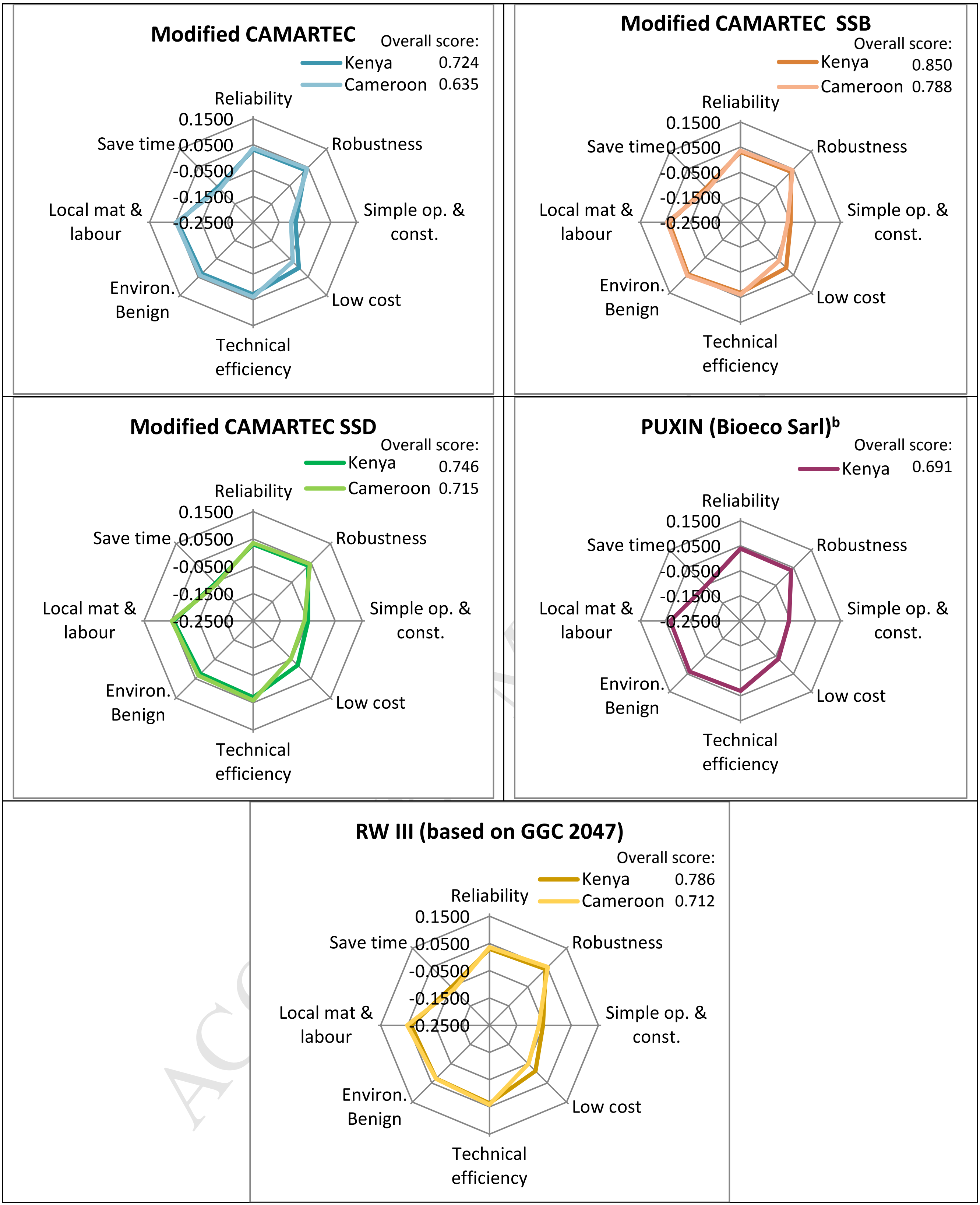
[b] Based on a discount rate of 10% [127]

[c] Based on an exchange rate of 1 USD = 588.44 FCFA (current July 2016)

Score weighting based on priority criteria rating[a]

Reliability = 3, Robustness = 3, Simple operation = 5, Low cost = 5, Technical efficiency= 3, Environmentally benign = 3, Local materials and labour = 3, Save time = 5





[a] 1=not important, 3=moderately important, 5=extremely important

[b] The AGAMA BiogasPro, KENBIM and PUXIN (Bioeco Sarl) desings were not considered feasible for an average rural Cameroonian household as their depth for underground consturction exceeds the limit set by the groundwater level

Figure 1: Multi-criteria analysis of biogas systems design options for rural Kenyan and Cameroonian households

3.2 Conclusions

The OBSDM applies the TOPSIS MCDA method to compare different types of biogas system designs with the optimal design being identified as the one which best fits the context and priorities of the intended user. This was reflected by applying the model to case studies of rural households in Kenya, were there was limited water supply, and rural households in Cameroon, which had lower disposable incomes and higher energy and fertiliser costs. The optimal designs identified by the model for these case studies was an innovative Modified CAMARTEC digester design, the stabilised soil block digester. Modified CAMARTEC SSBs are less expensive and energy intensive through using stabilised soil blocks. The output design details for these systems provided reasonable estimates of the expected biogas production potential and resulting savings in firewood consumption. Estimates of chemical fertiliser replacement in the OBSDM were reflective of those stated in the Kenyan survey. The accuracy of installation and cost estimates, can be improved in the model by using local material and labour prices. The database of biogas system designs in the OBSDM is not exhaustive and can be extended to include more biodigester types available in SSA. Further research to validate the OBSDM is required, including a sensitivity analysis of key input parameters. Overall, the results from the OBSDM highlight its effectiveness as a tool to identify the most appropriate biogas system design based on the context and priorities of an intended user.

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Highlights

- Model enables holistic first assessment of biogas system designs in SSA
- User-defined priorities of sustainability criteria help identify the optimal design
- Tailoring designs to user context helps ensure sustainable and long term system use
- Innovative designs minimising water use and costly materials are imperative for SSA