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Research article

Multiple-criteria decision analysis techniques for anaerobic digester technology assessment

Amsalu Tolessa [a,b,c,*], Neill J. Goosen [a,b], Tobias M. Louw [a]

[a] Department of Chemical Engineering, Stellenbosch University, Private Bag X1, Matieland, 7602, Stellenbosch, South Africa
[b] The African Research Universities Alliance (ARUA) Centre of Excellence in Energy, Stellenbosch University, Private Bag X1, Matieland, Stellenbosch, 7602, South Africa
[c] Forest Products Innovation Center of Excellence (FPICE), Ethiopia Forestry Development (EFD), Addis Ababa, Ethiopia

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ABSTRACT

Effective decision-making requires the evaluation of several criteria rather than a single, preferred criterion. The best decision options (alternatives) are recommended to decision-makers when a multi-criteria decision problem is addressed. This study develops a multi-criteria selection method for the assessment of small-scale anaerobic digester technology by combining two existing methods. The Simple Multi-Attribute Rating Technique (SMART) and the Analytical Hierarchy Process (AHP) approaches of multiple-criteria decision analysis were used as a decision support tool, and the preferred anaerobic digester technology was selected from a list of eleven potential small-scale digester technologies used in low to middle-income countries. These techniques were applied under two scenarios for a case study in the South African smallholder farmers. Scenario 1 involves a subsistence smallholder farming context, while scenario 2 involves a commercially oriented smallholder farming context. The overall results revealed that the DIY Biobag and Puxin digester design models achieved 82.1 and 73.7 % preference in comparison to other digester technologies for scenarios 1 and 2, respectively. The Biobag digester technology achieved the highest ranking, which is consistent with the significant cost advantage and technical characteristics of the technology. However, for those households with sufficient access to funds for the initial expenditure, the method identifies the Puxin digester as the most appropriate alternative, excluding cases where underground construction is not possible. The AGAMA BiogasPro digester was ranked in the second position in both scenarios. A sensitivity analysis was conducted to determine the effect of changes in the assessment criteria weights and found the selected alternatives stable and robust. Finally, it can be concluded that the developed technology selection model contributed a knowledge-based framework to be used in various situations by different decision-makers, thereby providing a method applicable to particular local conditions to identify the most suitable technology choices.

1. Introduction

Small-scale anaerobic digester (AD) technologies are considered as sustainable and clean technologies that can benefit households in rural areas to satisfy their basic energy demands and enhance living conditions [1]. The use of biomass to energy conversion

* Corresponding author. Forest Products Innovation Center of Excellence (FPICE), Ethiopia Forestry Development (EFD), Addis Ababa, Ethiopia.
E-mail address: amsa.tola@gmail.com (A. Tolessa).

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technologies is one of the most promising sustainable energy choices for integrating small-scale energy production plants for clean energy generation in rural areas using off-grid technology [2–5]. Biogas produced via AD can provide renewable energy, while the organic fertilizer produced from AD can also help to alleviate rural poverty by enhancing agricultural productivity and maintaining better health [6]. Using clean technology can also help alleviate environmental stress by lowering greenhouse gas (GHG) emissions, water and soil pollution, and deforestation [7–10]. Furthermore, this technology represents one of the few small-scale technologies that could enhance the technical feasibility of decentralized development in low to middle-income countries (LMICs) [4]. However, the use and adoption of AD in smallholder farming systems, where it was expected to have an impact, are very low in Africa [11–13]. Despite the potential advantages, small-scale AD technology uptake in Africa has been slow, and this is partially linked to poor technology selection. In several cases, small-scale AD technology projects are conducted with limited systematic planning and technology selection and without considering the availability of local technical knowledge and skills, and environmental and socio-economic perspectives [7]. This leads to digester abandonment and failure in implementing small-scale biogas projects in remote rural areas of LMICs [14]. These are the exact areas that could also stand to significantly benefit from such technologies.

Technology selection methods require the assessment of several analytical (intangible) and economic (tangible) factors in decision support conditions [15]. Obtaining the exact analysis data or quantifying those intangible and/or tangible factors is challenging [15], leading to poor decision-making when selecting technologies for implementation in a specific region. To improve decision-making, a systematic approach is necessary to address technology selection assessment factors (criteria), in order to make the most suitable selection that satisfies the specific requirements of the region where the technology is implemented. To systematically solve such a multi-criteria problem, multi-criteria decision analysis (MCDA) is required, which can be used for anaerobic digester technology selection [1,16,17].

The MCDA technique is a popular technology selection approach, which offers a means to systematically frame and assess complex multi-criteria decision problems [18,19]. Several MCDA techniques are used in many decision-making frameworks, and it has been reported that different approaches may yield different analysis findings [20]. Of those techniques, the Analytical Hierarchy Process (AHP) and the Simple Multi-Attribute Rating Technique (SMART) approaches are considered in this paper, since these techniques are the more effective and flexible in the assessment, selection, and design of sustainable projects, eliminating failures in their application and management [7,21–23].

The AHP is a flexible method used to organise and analyse complex decision problems based on their relative preference [19,23]. The main feature of this technique is the use of pair-to-pair comparisons, which are employed both to assess selection criteria weights that are utilized in decision analysis and to compare the options (alternatives) concerning the numerous criteria decided on during planning. This method has been broadly utilized and applied successfully to numerous practical problems [16,21,22,24–26]. Some of the advantages of this technique are that it is not data-intensive; scalable and easy to utilize [19,22]. However, some of its drawbacks are interdependence problems between criteria and options; rank alteration in cases when applied to rank a new type of alternative against other known ones and it can lead to inconsistencies between criteria ranking and decision [22,23,27].

In the SMART approach, options are prioritized according to ratings that are assigned from the natural scales of attributes (criteria) directly [23,27,28]. The major benefits of SMART compared to other MCDA approaches are increased flexibility and simplicity, requires less effort in the decision-making process as the results are computed using a simple additive weighting method and it also permits any type of weight rating methods (e.g., absolute, relative, etc.) [22]. The main advantage of this approach over the AHP is that the judgment analysis technique is built independently of the options. Hence the options ratings are not relative and consequently, the introduction of a new type of options doesn't affect the scores of other known alternatives [23,27,28]. Also, it can be employed for any number of criteria or alternatives without restriction. Its disadvantage is that the technique for determining work may not be convenient considering the intricate framework [22].

Anaerobic digestion is a well-established technology for waste valorisation and bioenergy production, but the adoption thereof is low in the context of smallholder farming in Africa. Smallholder farmers play a significant role in many economies around the globe, albeit their economic contributions are not always acknowledged, particularly in Africa [29]. Their farming practices are currently confronted with several difficulties, including low productivity, a lack of access to reliable, inexpensive, and high-quality energy services, and problems related to climate change [30]. In South Africa, there are numerous different general definitions for smallholder farmers and the terminology used to refer to them has been inconsistent. This terminology has usually been related to the specific number of farmers in a specific group, which makes classification difficult [31]. The term "smallholder" refers to the overall number of households situated in rural areas and former homelands involved in farming activities and characterized by subsistence and non-commercial farming practices [32–34]. The term smallholder is often also used in a broader sense to refer to the total number of farmers or households involved in any agricultural production on a relatively small scale [31,33]. This broad group of farming households or small-scale farmers can be subdivided into two groups according to the South African National Department of Agriculture, Forestry and Fisheries [35]. The first group of farmers, known as 'subsistence farmers', are formally defined as those farming households involved in agriculture which only produce agricultural goods for their own household consumption [35]. The second group of farmers known as 'emerging smallholder farmers' are defined as those that are situated in former homeland areas, therefore including households that are commercially inclined by marketing their produce [36]. The overall objective of this study is to employ decision support tools in the technology selection for the most suitable AD technologies to be used in smallholder farming systems based on their measurable attributes.

The AHP and SMART approaches of MCDA were combined in this study to develop a robust decision support method to determine the most preferable AD technology from among many alternatives, given a particular local context. This method is likely to be particularly useful to decision-makers and researchers in designing and planning frameworks for projects, as the combined method draws on the individual strengths of each. The work is significant as it develops, demonstrates, and tests a method that can enable navigation of a scenario where a large number of technologies are available, and the most appropriate one needs to be found given multiple criteria linked to a particular set of local conditions. It is demonstrated particularly for selecting the most appropriate small-scale AD technology in a South African context but is easily adaptable to other countries and other technology selection scenarios not related to AD. This method can eliminate poor technology selection, and therefore (if followed) can be an important tool for decision-makers at the start of policy-making or scientific project roll-out, to enable wider societal uptake of AD technology. Moreover, this work can also serve as a means to ensure structured approaches are followed in the implementation of renewable energy projects, thereby decreasing the number of poorly planned and/or failed projects.

2. Methodology

2.1. Technology selection model description

The model used for the technology selection comprised numerous procedural steps as presented in Fig. 1, based on [25]. Following the goal definition (the choice of the most appropriate small-scale AD technology for smallholder settings in South Africa), the first step was the formulation of a list of various potential AD technologies, based on an intensive literature review (such as existing literature models, locally available reports, websites, and other publicly available sources). The reviews were utilized to compose and select suitable technologies for the case study, as it affect the techno-economic situation overall. A total number of 20 AD technologies implemented in low to middle-income countries were reviewed, from which 11 were selected based on their scale and data availability as alternatives in the MCDA procedure [37]. Following this, associated quantitative and qualitative information were collected for the identified alternatives. The AD technologies were used as the options from which evaluation would be carried out and judgments built on the most preferred technology. In this step, two specific scenarios were also formulated for small-scale AD selection cases.

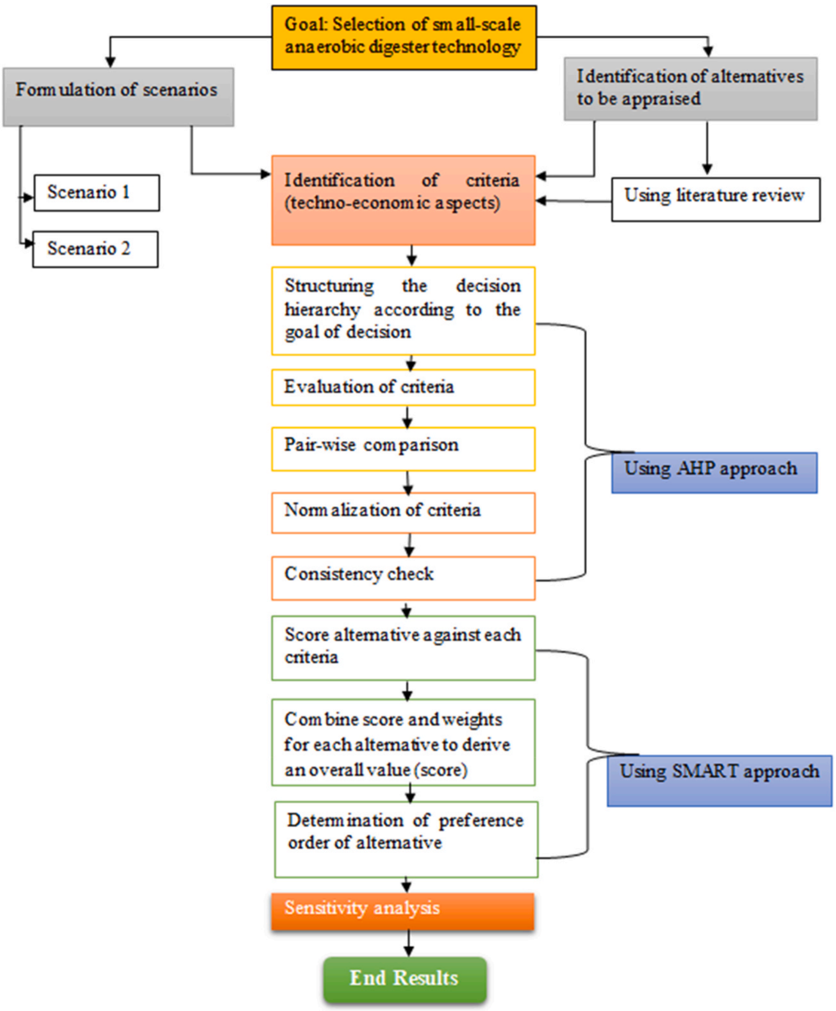

Fig. 1. MCDA process in technology selection decision making.

The two specific scenarios were (1) AD technology selection in a subsistence smallholder farm household context and (2) AD technology selection in a commercially oriented (emerging) smallholder farm household context. The scenarios considered were developed based on the statistics of South Africa [38] and other previously published papers [34,39]. The first scenario, which is technology selection in a subsistence farm household context, corresponds to the condition in which smallholder farmers have limited technical expertise, which can pose serious challenges in accessing valuable proper organizations that disseminate knowledge on technological aspects [39]. In this scenario, a large number of smallholder farming households are not capacitated financially (low household income) or infrastructurally. The second scenario consists of a situation in which smallholder farmers do not produce solely for subsistence but also to sell part of their produce, although few aspire to fully commercialize their products. These farmers typically also have some access to technical skills training and some necessary infrastructure. Table 1 shows the main features of both scenarios.

Next, the key selection criteria that are important to the stated technology selection goals were identified. Numerous criteria affect the selection process of any technology, but some criteria tend to dominate the decision process. However, technology selection is commonly done based on a number of techno-economic considerations [24]. Selection criteria should also include those perspectives which reflect concerns relevant to the decision problem. Criteria selection must reflect the concerns and preferences of stakeholders and decision-makers [42]. In this study, specific selection criteria used for the evaluation of the 11 selected AD technologies in the multi-criteria decision analysis procedure were chosen taking into account small-scale AD programs already implemented in rural communities of LMICs [17,24,27,43,44]. However, in order to ensure their relevance in the context of smallholder settings in South Africa, the criteria used in this study were chosen based on previous studies conducted in the country [37,43]. Furthermore, the local characteristics and relevance for the case study were also taken into consideration (to meet the objectives) when selecting the criteria, and an attempt was also made to pay attention to the stakeholders via the available literature review and other relevant publicly available documents and reports [14,45–47]. In this paper, a total of eight (8) important techno-economic aspects of technology selection criteria were identified, evaluated, and used for alternative digester selection processes under the developed scenarios. Table 2 presents the selected criteria lists.

The combined AHP and SMART approaches of a MCDA technique aim to attain a decisive goal from multiple options using a pre-selected/defined range of criteria [23].

2.2. Weighting assessment criteria using AHP approach

To rank the eight assessment criteria, the AHP-MCDA method was employed to perform a pairwise comparison among criteria that can be applied to choose the best product among all potential alternatives. The four steps of AHP include (1) construction of hierarchy; (2) pair-to-pair comparison of matrices; (3) determination of weight for each criterion via normalization procedure; and (4) combination of weight and consistency check [19]. This technique offers the evaluation of selection criteria that are utilized in the decision-making process and provides weighting value for all the selected criteria [48]. The selected criteria were assigned scores according to their level of importance/preference based on [7,24,27,46,49]. A matrix was generated through pairwise comparisons by using the standard preference scale set by Saaty [50] in a range of 1–9 as presented in Table 3, and criteria weights were obtained through calculations from the average normalized value. The pairwise comparison matrix was normalized by computing as per the method followed by Kasie [28] as presented in the appendix, Table A1.

Combining weights of the normalized values indicates that the sum of all weights must be equal to 1.00 using eq. (1).

$$\sum_{i=1}^{n} W_i = 1 \tag{1}$$

It is important to evaluate the degree of consistency, to avoid incorrect preferences during the execution of pairwise comparison and its order. To test the consistency of the pairwise comparison, the consistency ratio (CR) of judgments was calculated based on the method developed by Saaty [50]. In a pairwise comparison matrix, the consistency ratio shows the random likelihood of values being obtained [48]. The value of CR is less or equal to 0.10 (10 %) means that the degree of consistency is acceptable, if not, there are serious inconsistencies that may make the AHP method produce meaningless findings. In such a case, a revision of the pairwise comparison is

Table 1
Developed scenario of AD technology selection.

	Scenarios	Main variation factors
Scenario 1	Digester selection in a subsistence smallholder farming household context (those only produce agricultural goods for their own household consumption)	**Income, education, and infrastructure** Skill needed for construction & cost of digester • should be simple to install and requires little skills and initial training • the capital cost involved in purchasing and installing the technology should be low Digester size <10 m^3 [40,41]
Scenario 2	Digester selection in a commercially oriented smallholder farming household context (those marketing or sell part of their produce)	**Users need** Scalability or flexibility of digester capacity & suitability of substrate Digester size 10–30 m^3 [7,27]

Table 2
Perspectives and criteria for AD technology selection.

Perspectives	Criteria	Sub-criteria
Technical	Capacity/digester volume	Scalability
	Skills	Ease of construction
	Materials	Local availability of technologies (construction materials)
	Physical structure	Feedstock suitability
		Agitation method
		Temperature regulation
	Lifespan	Sturdiness
Economic	Capital cost	Initial cost of plant (construction)

Table 3
Description of preference scale for pair-wise comparison using AHP.

Level of preference	Numeric Score/Value
Equal	1
Equal to moderate	2
Moderate	3
Moderate to strong	4
Strong	5
Strong to very strong	6
Very strong	7
Very strong to extreme	8
Extreme	9

required [21,48,51].

The degree of consistency for the pairwise comparisons is calculated by the ratio of the consistency index (CI) to the random consistency index (RI). The consistency index was determined for the pairwise comparison matrix by using the eigenvalue as shown in eq. (2).

$$\lambda_{max} = 1 \Bigg/ n \sum_{i=1}^{n} X_i \Bigg/ W_i \tag{2}$$

Where, λ_{max} is the eigenvalue of the pairwise comparison matrix.

W_i is the normalized weight given for each criterion by using AHP.

X_i are values calculated from the generated pairwise comparison matrix (A) and criteria weights, as presented in appendix D, Table 10.15.

n is the number of criteria used for pairwise comparisons.

The consistency index (CI) was computed using eq. (3).

$$CI = (\lambda_{max} - n) / (n - 1) \tag{3}$$

The RI is obtained from a computer simulation of matrices with random values from the scale 1–9. It is constant for a $n \times n$ matrix; the average values for various n are shown in Table 4.

2.3. *Weighting digester technology alternatives using SMART approach*

After the consistency check, the SMART-MCDA technique was applied to score and rank the preference (performance) of all the AD technology alternatives against each assessment criterion. For all identified potential alternatives, a numeric score between 0 and 1 was given to indicate how well each alternative executed concerning a specific criterion using SMART, where a score of 0 implies nearly no satisfaction and 1 implies extremely high satisfaction. Then, an overall value (score) of options is computed as the sum of the total product of the options with corresponding criteria. Finally, an alternative with a higher overall score of Si indicates the highest rank which is the better decision alternative (the best digester technology) [52].

For each digester alternative D_i against each criterion C_j, the overall "score" S_i was computed by applying eq. (4):

$$S_i = \sum W_j D_{ij} \tag{4}$$

Table 4
The random average consistency indexes (RI) for various n [32].

Size of matrix (n)	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Table 5
Quantitative and qualitative attributes of the selected AD technology alternatives.

Criteria	Anaerobic Digester Alternatives									
	Fixed dome digester (brick and mortar)	Floating drum digester	Agama BiogasPro digester	Little green monster digester	EZ-digester	DIY BioBag digester	Puxin digester	Africa green energy technologies digester	Geomembrane digester	STANDARD digester	GREENBOX digester
Digester capacity (m^3)	10	60	6	2.5	1.5	10	10	10	35	30	From 100
Local availability (in the country)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
Material	Brick and mortar	Concrete structure	Prefabricated Polyfiber tank origin in South Africa	Prefabricated Polyethylene tank	Heavy duty rotor moulded plastic	PVC plastic bag	In-situ concrete	Concrete structure	Prefabricated Polyfiber tank origin in India	Prefabricated Polyfiber tank origin in England	On-site steel
Feedstock suitability	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Agitation method	None	None	Manual	None	None	None	Hydraulic	None	Manual	External hydraulic system	Incorporated
Temperature regulation	Constructed underground	Constructed Underground	Aboveground	Constructed Underground	Aboveground	Constructed Underground	Constructed Underground	Constructed Underground	Aboveground	Insulated	Insulated
Lifespan (years)	Up to 20	Up to 15	15	20	10+	Up to 15	30+	Up to 20	15	10	15
Cost of digester (R)	80 000	350 000	45 000	15 000	12 000	16 000	60 000	–	180 000	210 000	1 200 000
Cost of digester per m^3	8000	5800	7500	6000	8000	1600	6000	–	5140	7000	12 000
References	[14,43,55,56]	[27,55,56]	[27,43,57]	[43,58–60]	[43,58,59,61]	[43,46,58,59]	[27,43,58]	[27,43]	[27]	[27]	[27,62]

Note: Local availability of the technologies differ due to the fact some are imported, some are fully manufactured/constructed and others are not available in the country. Construction material and their designs were taken into consideration for substrate suitability. Digester capacity (scalability) - availability of flexible sizes for the stated scenarios was also taken into consideration.

where, W_j is the normalized weight allocated to each assessment criterion C_j using AHP.

D_{ij} is the scored preference of the digester alternative D_i against each criterion C_j using SMART.

2.4. Sensitivity analysis

The results from a MCDA can only be useful if it is stable [16,50]. Hence, a sensitivity analysis was conducted to evaluate the effect of changing selection criteria weights, to see their impact on the rankings and the proposed technology selection scenarios. If the alternatives ranking does not alter, the outcomes are supposed to be robust [25].

A sensitivity analysis was conducted taking into consideration that the opinions of decision-makers may differ, which may in turn affect the ranking they assign to different criteria. It was carried out for marginal situations of criteria weighting, to evaluate the effect of each criterion and group of criteria, due to bias of the preference in pair-wise comparison of criteria. Therefore, five sensitivity analysis (SA) cases were assessed.

- SA Case 1: All the selection criteria have an equal 12.5 % weight.
- SA Case 2: The group of technical criteria (availability, construction, suitability, scalability, lifespan, temperature, and agitation) has a 100 % weight in aggregate (each of them has a 14.29 % weight), while the economic criteria have a 0 % weight.
- SA Case 3: The economic criterion (digester cost) has a 100 % weight, while all other technical criteria have a 0 % weight.
- SA Case 4: The group of technical criteria weighs 50 % (each of them weighs 7.14 %), and the economic criterion (digester cost) weighs 50 %.
- SA Case 5: Five of the criteria (availability, cost, construction, suitability, and scalability) have a 20 % weight each and the others have a 0 % weight.

The criteria weighting sensitivity analysis cases used in this study are comparable to the ones conducted by other authors [25,53,54].

3. Results and discussion

Results of small-scale AD technology selection using eight different criteria are presented in this paper. A methodological study combining AHP and SMART approaches of MCDA was used to evaluate selection criteria, rank alternatives, and identify the best AD alternative among different models and designs under two scenarios, for implementation in smallholder farming systems. To determine the effect of changes in the assessment criteria weights sensitivity analysis was also conducted. According to the scale of AD, 11 small-scale digester technologies were considered. The developed lists of these alternative AD technologies are presented in Table 5. The following sections discuss a detailed description of the results.

3.1. Assessment criteria weighting via AHP approach

In this study, AHP was applied to assess the weight of each criterion, as it is preferable to other MCDA methods for comparison of criteria that are not more than 10 [28]. Table 6 presents the pairwise comparison matrix, to determine the selection criteria weights. The priority of all the eight criteria is combined to form normalized criteria values, which is named the normalized criteria matrix as presented in the appendix, Table A1.

Table 6
Preference matrix (A) or pair-wise comparison.

	Criteria	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
Scenario 1	**C-1**	1	1	1	3	3	5	7	3
	C-2	1	1	1	3	2	3	7	3
	C-3	1	1	1	3	2	3	5	3
	C-4	1/3	1/3	1/3	1	1/3	2	3	1/2
	C-5	1/3	1/2	1/2	3	1	3	5	2
	C-6	1/5	1/3	1/3	1/2	1/3	1	2	1/2
	C-7	1/7	1/7	1/5	1/3	1/5	1/2	1	1/3
	C-8	1/3	1/3	1/3	2	1/2	2	3	1
Scenario 2	**C-1**	1	2	3	1/2	4	3	5	1/2
	C-2	1/2	1	2	1/3	3	2	4	1/3
	C-3	1/3	1/2	1	1/4	2	1	3	1/4
	C-4	2	3	4	1	5	4	7	1
	C-5	1/4	1/3	1/2	1/5	1	1/2	2	1/5
	C-6	1/3	1/2	1	1/4	2	1	3	1/4
	C-7	1/5	1/4	1/3	1/7	1/2	1/3	1	1/7
	C-8	2	3	4	1	5	4	7	1

C-1 = Local availability C-2 = Digester cost C-3 = Easy of construction C-4= Substrate suitability C-5= Lifespan C-6= Temperature regulation ability C-7= Presence of agitation C-8= Scalability.

To check the pairwise comparison execution reliability, the CR was calculated. The consistency of the analysis of the pairwise comparisons revealed that it is reliable and acceptable as CR < 0.1 for both scenarios 1 and 2, indicating that overall consistency is satisfactory, as shown in Table 7. The consistency vector matrix generated and used for consistency index (CI) calculation is presented in the appendix, Table A2.

Following the acceptable consistency of the pair-wise comparison, the relative weights of criteria that are considered in the technology selection process concerning the goal for both scenarios were obtained and presented in Table 8. This result from the pair-wise comparison shows that for scenario 1, local availability of the technology (23.2 %), the initial cost of the digester (20.6 %), and ease of construction (19.9 %) followed by lifespan (12.2 %) have higher weight than all other criteria with the overall inconsistency of 2.4 %. Scenario 1 results are in accordance with the study performed by Ferrer-martí et al. [7] and Kuria et al. [49], as reported by high criteria weight for the availability of construction materials, ease of construction, lifespan, and initial investment cost relative to other technical criteria for small-scale anaerobic digesters. For scenario 2, capacity scalability and substrate suitability have equal criteria weight (26.0 %) followed by local availability (16.6 %) and cost (10.8 %) with an inconsistency of 1.3 %. Scenario 2 results are comparable to those generated by Njuguna et al. [23] and Kigozi et al. [27], except that they did not incorporate lifespan as a criterion. The presence of an agitation device has low criteria weight in both scenarios, which is expected since automated mixing is less important for small-scale plants where the substrate slurry can be mixed manually [27]. These criteria weights seem reasonable for the context mentioned in each scenario.

3.2. *Digester technology alternatives weighting via SMART approach*

After the selection criteria weight evaluation, scores were awarded to each technology alternative against the assessment criteria using the SMART technique, and an overall score for each alternative was calculated. The advantage of this approach is that all the alternatives can be assessed independently, and it is mainly suitable when introducing new criteria or options to the present comparison assessment and obsolete ones are rejected. This feature is crucial to increase, modify and reject alternatives without influencing the value of previously existing alternatives.

Fig. 2 presents the MCDA hierarchical framework considered in the selection of an alternative AD technology for the anaerobic digestion process, based on the selected criteria. This framework combines the advantage of AHP and SMART methods to conduct a MCDA for technology selection. All the selected criteria were evaluated against the goal using the AHP approach as discussed above, while all the alternatives were weighed against each criterion (which was evaluated using AHP) using the SMART approach.

Table 9 presents the score and performance of the 11 potential digester alternatives that were assessed against the eight selection criteria under the developed scenarios. Ranks of alternatives were calculated as a total summation of products of the options with corresponding criteria and a decision about the most suitable alternative is then made from the ranking. The overall normalized performance matrix of the AD alternative is available in the appendix, Table A3.

Table 10 presented the summarized overall scores and ranks of the eleven different AD alternatives compared against the selection criteria under both scenarios. An alternative with the highest overall score implies a better decision alternative.

From the combined AHP-SMART method results showed that DIY Biobag, AGAMA BiogasPro, and Puxin digesters appeared in the top three digester technologies for both scenarios. However, there are small changes in ranking priority between DIY Biobag and Puxin digesters, while the AGAMA BiogasPro digester maintained the same rank in both scenarios.

For scenario 1, the DIY Biobag digester ranked first with a ranking priority of 82.1 % followed by AGAMA BiogasPro and Puxin digesters with a ranking priority of 77.2 % and 75.5 % respectively. The reason for the DIY Biobag digester being top-ranked for scenario 1 is that it comes at the lowest cost when compared to other digester technologies. It represents the best-suited technology for rural areas and poor farmers as well [57–59]. Ease of construction, cost and local availability criteria are key factors in the success of AD implementation particularly in the subsistence smallholder farmer context, as these criteria are crucial to ensure that smallholder farmers have access to the technologies, and can afford the investment [45,46].

For scenario 2, the Puxin digester is top-ranked with a 73.7 % ranking priority followed by the AGAMA BiogasPro digester with a ranking priority of 70.4 %. This is comparable to the study conducted by Kigozi et al. [27] and Mutungwazi et al. [43], for households and pilot-scale (small facilities) digesters. The AGAMA BiogasPro digester maintained the same rank in both Scenarios and remains stable. However, this digester has an inflexible size, as it is produced in fixed volumes of 6 m^3. It also has a limitation in temperature regulation ability since it is built above-ground and lacks an agitation device, which reduces its total score to fall below that of the Puxin digester for scenario 2, while its higher cost reduces its score to fall below that of the DIY Biobag digester in scenario 1. The top three digesters are all available locally in South Africa, are constructed easily and are suitable for various feedstock options.

AGET, Fixed dome, and Geo-membrane digesters maintained the same rank of 6, 7, and 8 respectively in both scenarios, while EZ and LGM digesters only changed by a rank of 1 place. In both scenarios, the worst options of alternatives are the floating drum digester, STANDARD, and Greenbox digesters, which is a result of the fact these technologies are either fully or partially unavailable locally and

Table 7
Results of consistency check analysis.

	Overall CI	Overall RI (for n = 8)	Overall CR
Scenario 1	0.03359	1.41	0.024
Scenario 2	0.01889	1.41	0.013

RI is random consistence index.

Table 8
Summary of the criteria weights for Scenario 1 and 2.

Criteria	Weight (W)	
	Scenario 1	Scenario 2
Local availability (C-1)	0.232	0.166
Digester cost (C-2)	0.206	0.108
Easy of construction (C-3)	0.199	0.068
Substrate suitability (C-4)	0.078	0.260
Lifespan (C-5)	0.122	0.044
Temperature regulation ability (C-6)	0.050	0.068
Presence of agitation (C-7)	0.028	0.028
Scalability (C-8)	0.084	0.260

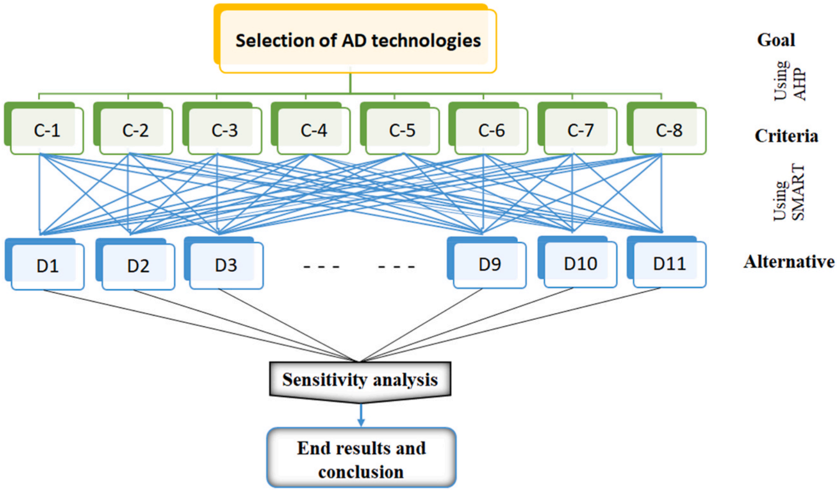

Fig. 2. Relation of goal, criteria, and digester alternatives in a combined AHP-SMART framework.

Table 9
Scores for each alternative against criteria.

	Criteria	Weight	AD Alternative										
			D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Scenario 1	C-1	0.232	0.30	0.00	1.00	0.65	0.65	0.90	0.80	0.50	0.00	0.00	0.30
	C-2	0.206	0.60	0.75	0.60	0.60	0.60	1.00	0.65	0.50	0.80	0.65	0.10
	C-3	0.199	0.50	0.70	1.00	0.60	0.90	0.90	0.80	0.65	0.70	0.75	0.40
	C-4	0.078	0.70	0.20	0.65	0.60	0.60	0.60	0.70	0.60	0.80	0.20	0.85
	C-5	0.122	0.80	0.80	0.80	0.85	0.70	0.80	1.00	0.85	0.80	0.60	0.80
	C-6	0.050	0.50	0.50	0.10	0.50	0.10	0.50	0.50	0.50	0.30	0.65	0.70
	C-7	0.028	0.10	0.10	0.20	0.10	0.20	0.10	0.40	0.10	0.30	0.60	0.80
	C-8	0.084	0.65	0.10	0.70	0.80	0.80	0.65	0.75	0.65	0.20	0.20	0.00
	$S_i = \sum W_j D_{ij}$		***0.53***	***0.44***	***0.77***	***0.64***	***0.66***	***0.82***	***0.76***	***0.58***	***0.50***	***0.43***	***0.39***
	Rank		***7***	***9***	***2***	***5***	***4***	***1***	***3***	***6***	***8***	***10***	***11***
Scenario 2	C-1	0.166	0.30	0.00	1.00	0.65	0.65	0.90	0.80	0.50	0.00	0.00	0.30
	C-2	0.108	0.60	0.75	0.60	0.60	0.60	1.00	0.65	0.50	0.80	0.65	0.10
	C-3	0.068	0.50	0.70	1.00	0.60	0.90	0.90	0.80	0.60	0.70	0.75	0.40
	C-4	0.260	0.70	0.20	0.65	0.60	0.60	0.60	0.70	0.60	0.80	0.10	0.85
	C-5	0.044	0.80	0.80	0.80	0.85	0.70	0.80	1.00	0.85	0.80	0.60	0.80
	C-6	0.068	0.50	0.50	0.20	0.50	0.20	0.50	0.50	0.50	0.30	0.65	0.70
	C-7	0.028	0.10	0.10	0.20	0.10	0.20	0.10	0.40	0.10	0.30	0.60	0.80
	C-8	0.260	0.60	0.10	0.70	0.55	0.55	0.60	0.80	0.60	0.20	0.20	0.00
	$S_i = \sum W_j D_{ij}$		***0.56***	***0.28***	***0.70***	***0.59***	***0.58***	***0.70***	***0.74***	***0.56***	***0.46***	***0.29***	***0.41***
	Rank		***7***	***11***	***2***	***4***	***5***	***3***	***1***	***6***	***8***	***10***	***9***

D1 = Fixed dome digester (brick and mortar), D2 = Floating drum digester, D3 = AGAMA BiogasPro digester, D4 = Little green monster (LGM) digester, D5 = EZ-digester, D6 = DIY BioBag digester, D7 = Puxin digester, D8 = Africa green energy technologies (AGET) digester, D9 = Geo-membrane digester, D10 = STANDARD digester, and D11 = GREENBOX digester.

Table 10
Summary of the overall score and ranking of AD alternatives.

AD alternatives	Scenario 1		Scenario 2	
	Rank	Score	Rank	Score
DIY bag digester (D6)	1	0.821	3	0.703
AGAMA BiogasPro digester (D3)	2	0.772	2	0.704
Puxin digester (D7)	3	0.755	1	0.737
EZ-digester (D5)	4	0.664	5	0.583
LGM digester (D4)	5	0.639	4	0.587
AGET digester (D8)	6	0.581	6	0.564
Fixed dome digester (D1)	7	0.527	7	0.559
Geo-membrane digester (D9)	8	0.504	8	0.458
Floating drum digester (D2)	9	0.443	11	0.279
STANDARD digester (D10)	10	0.430	10	0.287
Greenbox digester (D11)	11	0.391	9	0.414

are not scalable to the required size ranges for each investigated scenario, which reduces their total scores and increases those of technologies that meet these criteria better.

3.3. Sensitivity analysis and ranking AD alternatives

Table 11 summarizes the overall digester alternative ranking results of the sensitivity analysis compared to the original analysis rank, whilst the overall sensitivity analysis scores are presented in the appendix, Table A4 and Table A5.

The following section discusses a detailed description of the sensitivity analysis cases result compared to the original analysis (OA).

SA Case 1: If all selection criteria are assumed to have an equal 12.5 % weight (see Table 11, SA1), the alternative ranking of the sensitivity analysis was slightly changed relative to the original rank (OA) for both scenarios. However, the alternative ranks in scenario 2 are more stable as 64 % of the ranks are not changed and 36 % are only changed by a rank of 1 place. In scenario 1, 27.3 % of alternatives maintained the same rank and 45.4 % were only changed by a rank of 1 place, while 27.3 % were changed by a rank of up to 3 places. In both scenarios, the best-performing alternative is the Puxin digester. DIY Biobag and AGAMA BiogasPro digesters are in the top three technologies in both scenarios. In case 1, the worst option of an alternative in both scenarios is a floating drum digester followed by STANDARD and Geomembrane digesters, which is a result of the fact these technologies are not locally available.

SA Case 2: In the case where a group of technical factors has a 100 % weight, while economic criterion has a 0 % weight (see Table 11, SA2), the alternative ranking was slightly changed for the majority of the alternatives in scenario 1 and not changed for the majority of alternatives in scenario 2 compared to the original rank (OA). In scenario 2, the top four technologies are 100 % stable compared to the original rank. The results of Case 2 sensitivity analysis show that the Puxin digester is more stable and ranked first place in both scenarios. DIY Biobag and AGAMA BiogasPro digesters are ranked second with equal priority ranking for scenario 1, while AGAMA BiogasPro digester is ranked second and DIY Biobag digester is ranked third for scenario 2. Like Case 1, the Floating drum digester ranked last in both scenarios followed by STANDARD and Geomembrane digesters.

SA Case 3: In case the economic factor has a 100 % weight and all other technical criteria have a 0 % weight (see Table 11, SA3), the analysis results show that there is a substantial rank alteration for most of the alternatives in both scenarios. However, the affordable option DIY Biobag digester appears as the most stable and the top-rank alternative in both scenarios as this scenario specifically analyses the context of low economic resources. With regard to financial perspectives, the capital cost involved in purchasing and installing the technology seemed to be the most vital one. In fact, in rural areas of LMICs, it is considered the most substantial challenge for widespread small-scale digester use [45,46]. Geomembrane and Floating drum digesters are ranked second and third. In the case of 100 % economic criteria weighting, the Greenbox digester ranked worst under both scenarios due to the fact that it is technically

Table 11
Summary of the ranking of sensitivity analysis results.

AD alternatives	Rank for Scenario 1						Rank for Scenario 2					
	OA	SA1	SA2	SA3	SA4	SA5	*OA*	SA1	SA2	SA3	SA4	SA5
DIY bag digester	***1***	2	2	1	1	1	***3***	2	3	1	1	1
AGAMA BiogasPro digester	***2***	3	2	6	3	2	***2***	3	2	6	3	2
Puxin digester	***3***	1	1	4	2	3	***1***	1	1	4	2	3
EZ-digester	***4***	5	5	6	6	4	***5***	5	6	6	6	4
LGM digester	***5***	4	4	6	5	5	***4***	4	4	6	5	4
AGET digester	***6***	6	6	10	10	6	***6***	6	7	10	10	6
Fixed dome digester	***7***	7	8	6	7	7	***7***	7	8	6	7	7
Geo-membrane digester	***8***	9	9	2	4	8	***8***	9	9	2	4	8
Floating drum digester	***9***	11	11	3	8	9	***11***	11	11	3	8	9
STANDARD digester	***10***	10	10	4	9	10	***10***	10	10	4	9	10
Greenbox digester	***11***	8	6	11	11	11	***9***	8	4	11	11	11

OA stands for the original analysis, S_i stands for Sensitivity Analysis Case i.

advanced and comes at the highest cost, is not easily constructed, and is not scalable to the required size.

SA Case 4: The group of technical criteria weighs 50 % (each of them weighs 7.14 %), and the economic criterion (digester cost) weighs 50 % (see Table 11, SA4), the alternative ranking was slightly changed in both scenarios for some alternatives. DIY Biobag digester remains stable and ranked in the first position in both scenarios followed by Puxin and AGAMA BiogasPro digesters (see Table 11, SA4). Greenbox digester ranked as the worst option in both scenarios.

SA Case 5: In the case where a group of five techno-economic criteria (availability, cost, construction, suitability, and scalability) have a 20 % weight each and the others have a 0 % weight, the alternative ranking was not changed for scenario 1, while scenario 2 shows a slight change for some alternatives (see Table 11, SA5). DIY Biobag digester is ranked the best performing and stable alternative in both scenarios like in Case 3 and 4. AGAMA BiogasPro and Puxin digester ranked second and third in both scenarios.

The overall conclusion of sensitivity analysis results revealed that the DIY Biobag digester ranked as the most preferable alternative as presented in Fig. 3. It ranked in the first position in most cases (60 %, see Table 12) when priorities are given to economic criteria (SA3), 50 % economic and 50 % technical criteria (SA4), and a selected group of criteria (SA5) in both scenarios. Table 12 revealed that this digester model is also the most stable solution under whichever criteria weighting in terms of rank. The Puxin digester is ranked second overall since it ranked in the first position under equal criteria weightings (SA1) as well as when technical criteria weighting takes preference (SA2). AGAMA BiogasPro digester ranked third in both scenarios. Floating drum, STANDARD, Greenbox, Geomembrane and AGET digesters have the greatest fluctuation in their ranking priorities, whereas Floating drum and Greenbox digesters were the most stable to rank fluctuations. The overall sensitivity analysis revealed that the priority ranking of the alternative is robust for the top three technologies with little rank variations and comparable to results obtained by Kigozi et al. [27] and Mutungwazi et al. [43].

The results of this study reveal that the AHP and SMART approaches can be combined to develop a robust decision analysis tool to determine the most preferable AD technology from among several alternatives, given a particular local context. This tool is likely to be particularly useful to decision-makers and researchers to design planning frameworks for projects, as the combined method draws on the individual strengths of each method. Applying a single technique cannot always be expected to result in a substantial change in all features [28]. This study has employed AHP to prioritize the assessment criteria, while SMART was used to score the entire technology alternative's performance against each criterion to optimize their benefit. Thus, it can be concluded that AHP and SMART can be used in combination to determine the best technology rather than applying these methods independently. In this study, some of these advantages are.

- The method was applied under a range of different conditions, and the rankings consistently agreed with the known technology characteristics;
- The method has a built-in mechanism (the CR value) to check that results are consistent;
- The method calculates 'objective' weightings, and therefore eliminates 'subjective' bias that happens when weightings are assigned to criteria;
- The method is useful to take a structured approach to help solve the complex problem of appropriate technology selection by considering multiple criteria; and
- The method can also easily be applied to rank a new type of alternative against other known ones, in order to determine whether it is a viable technology alternative in different scenarios.

Likewise, the method has some shortcomings which include.

- The method requires a good definition of each specific project scenario due to the fact that the ranking is also likely to change if the scenario changes. In turn, a clear project definition requires inputs from somebody experienced in the technology, and also somebody who knows the specific local context and the needs and circumstances of the final beneficiaries, in order to fully define the project. Requiring input from so many stakeholders may make it complex and time-consuming to arrive at a rigorous project definition.
- The final operator of the procedure needs to be well-trained in it, in order to allow rigorous and correct manipulation of inputs, and interpretation of the various results and numbers (both intermediate and final).

The study was wholly carried out *in-silico* to demonstrate the power of the combined MCDA approach to reach key conclusions and provide directions for further research and policy recommendations. However, due to the *in-silico* nature of the study, one of its main limitations is the fact that the criteria were chosen based on the literature to take into account the concerns and preferences of stakeholders and decision-makers, even though the significance of stakeholder buy-in to the criteria and their validation with stakeholders is appropriate. In this study, future research is recommended on the applicability of selected alternatives on-site and to develop and/or adapt the most suitable small-scale AD technologies according to the local situations and demands through working with potential users and stakeholders. Besides, existing new AD technologies could be added to the list of alternative technologies studied in this paper. It is also recommended to perform further analysis on improving and expanding the MCDA tool by involving local experts within the farming sector, local communities, or relevant stakeholders in choosing additional criteria for social sustainability, which are specific to LMICs and refine the selection criteria best suited the smallholder context. This could be done to identify suitable technology and maximize favourable techno-economic results as well as technology uptake.

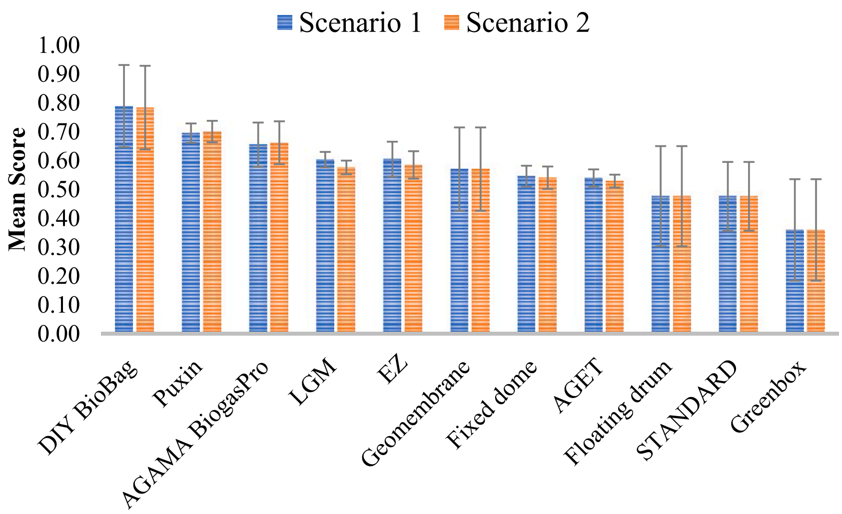

Fig. 3. Overall mean score of AD alternatives for five different cases of criteria weight.

Table 12
Summary of the rank frequency of AD alternatives for the aggregate sensitivity analysis results (5 cases and 2 scenarios).

AD Alternative	Rank										
	1	2	3	4	5	6	7	8	9	10	11
DIY bag digester	60 %	30 %	10 %	–	–	–	–	–	–	–	–
Puxin digester	40 %	20 %	20 %	20 %	–	–	–	–	–	–	–
AGAMA BiogasPro digester	–	40 %	40 %	–	–	20 %	–	–	–	–	–
EZ-digester	–	–	–	20 %	30 %	50 %	–	–	–	–	–
LGM digester	–	–	–	50 %	30 %	20 %	–	–	–	–	–
AGET digester	–	–	–	–	–	50 %	10 %	–	–	40 %	–
Fixed dome digester	–	–	–	–	–	20 %	60 %	20 %	–	–	–
Geo-membrane digester	–	–	–	20 %	–	–	–	20 %	40 %	–	–
Floating drum digester	–	–	20 %	–	–	–	–	20 %	20 %	–	40 %
STANDARD digester	–	–	–	20 %	–	–	–	–	20 %	60 %	–
Greenbox digester	–	–	–	10 %	–	10 %	–	20 %	–	–	60 %

4. Conclusion

The Analytical Hierarchy Process (AHP) and the Simple Multi-Attribute Rating Technique (SMART) were successfully combined into a robust multi-criteria analysis method, to determine the best anaerobic digestion technologies from multiple options, and for several different scenarios, within smallholder farming systems in South Africa. The method consistently accords the highest ranking to the Biobag digester technology from a list of 11 potential small-scale digesters used in LMICs. This ranking is consistent with the significant cost advantage of technical characteristics of the technology; however, for those households who have sufficient access to capital for the initial investment, the method identifies the Puxin digester as the most appropriate alternative, excluded in cases where underground construction is not possible. In such cases, the BiogasPro digester would be preferred since its construction mode is above-ground. This study recommended further analysis to fully incorporate local stakeholder opinions into the criteria selection and their validation with stakeholders although the findings are in line with previous studies. The findings demonstrated that AHP and SMART can be combined to choose the best technology, as opposed to using both techniques independently. The approach can be used in various situations as it is flexible and easy to apply when comparing new alternatives with well-established ones. It can also be used to evaluate whether a technology option is workable in various contexts and help with the challenging task of choosing the finest technologies. The study provides suggestions to professionals and researchers to apply AHP-SMART methodology techniques when analysing multiple, complicated and conflicting decision-making problems.

The developed technology selection method contributed a knowledge-based framework for the choice of the most appropriate technology from numerous options, given local conditions and constraints, and is likely to be useful to various decision-makers. Given the potential advantages of integrating small-scale anaerobic digestion technology into smallholder farming systems, continuous research and analysis of small-scale anaerobic digesters in Africa is recommended.

CRediT authorship contribution statement

Amsalu Tolessa: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Neill J.**

Goosen: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition. **Tobias M. Louw:** Writing – review & editing, Visualization, Validation, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary information

Table A1
Normalized criteria matrix and weight.

	Criteria	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	Total	Mean (W)
Scenario 1	C-1	0.230	0.215	0.213	0.204	0.315	0.256	0.200	0.225	1.859	0.232
	C-2	0.230	0.215	0.213	0.204	0.210	0.154	0.200	0.225	1.651	0.206
	C-3	0.230	0.215	0.213	0.204	0.210	0.154	0.143	0.225	1.594	0.199
	C-4	0.077	0.072	0.071	0.068	0.052	0.103	0.143	0.038	0.623	0.078
	C-5	0.077	0.108	0.106	0.136	0.105	0.154	0.143	0.150	0.979	0.122
	C-6	0.046	0.072	0.071	0.034	0.035	0.051	0.057	0.038	0.404	0.050
	C-7	0.033	0.031	0.043	0.014	0.021	0.026	0.029	0.025	0.220	0.028
	C-8	0.076	0.072	0.071	0.136	0.052	0.103	0.086	0.075	0.670	0.084
Scenario 2	C-1	0.151	0.189	0.189	0.136	0.178	0.189	0.156	0.136	1.325	0.166
	C-2	0.076	0.094	0.126	0.091	0.133	0.126	0.125	0.091	0.862	0.108
	C-3	0.050	0.047	0.063	0.068	0.089	0.063	0.094	0.068	0.543	0.068
	C-4	0.302	0.283	0.253	0.272	0.222	0.253	0.219	0.272	2.076	0.260
	C-5	0.038	0.031	0.032	0.054	0.044	0.032	0.063	0.054	0.348	0.044
	C-6	0.050	0.047	0.063	0.068	0.089	0.063	0.094	0.068	0.543	0.068
	C-7	0.030	0.024	0.021	0.039	0.022	0.021	0.031	0.039	0.227	0.028
	C-8	0.302	0.283	0.253	0.272	0.222	0.253	0.219	0.272	2.076	0.260

C-1 = Local availability C-2= Cost C-3 = Easy of construction C-4= Substrate suitability C-5= Lifespan C-6= Temperature regulation ability C-7= Presence of agitation C-8= Scalability.

Table A2
Consistency vector matrix calculated from performance matrix (A)* and criteria weights (W).

		C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	Total (X)	W	X/W
Scenario 1	C-1	0.232	0.206	0.199	0.234	0.367	0.252	0.193	0.251	1.935	0.232	8.327
	C-2	0.232	0.206	0.199	0.234	0.245	0.151	0.193	0.251	1.712	0.206	8.291
	C-3	0.232	0.206	0.199	0.234	0.245	0.151	0.138	0.251	1.657	0.199	8.312
	C-4	0.077	0.069	0.066	0.078	0.061	0.101	0.138	0.042	0.632	0.078	8.117
	C-5	0.077	0.103	0.100	0.156	0.122	0.151	0.138	0.168	1.015	0.122	8.296
	C-6	0.046	0.069	0.066	0.039	0.041	0.050	0.055	0.042	0.409	0.050	8.100
	C-7	0.033	0.030	0.040	0.016	0.024	0.025	0.028	0.028	0.223	0.028	8.116
	C-8	0.077	0.069	0.066	0.156	0.061	0.101	0.083	0.084	0.696	0.084	8.303
Scenario 2	C-1	0.166	0.216	0.203	0.130	0.174	0.203	0.142	0.130	1.364	0.166	8.233
	C-2	0.083	0.108	0.136	0.087	0.131	0.136	0.114	0.087	0.879	0.108	8.155
	C-3	0.055	0.054	0.068	0.065	0.087	0.068	0.085	0.065	0.547	0.068	8.061
	C-4	0.331	0.323	0.271	0.260	0.218	0.271	0.199	0.260	2.133	0.260	8.218
	C-5	0.041	0.036	0.034	0.052	0.044	0.034	0.057	0.052	0.349	0.044	8.025
	C-6	0.055	0.054	0.068	0.065	0.087	0.068	0.085	0.065	0.547	0.068	8.061
	C-7	0.033	0.027	0.023	0.037	0.022	0.023	0.028	0.037	0.230	0.028	8.086
	C-8	0.331	0.323	0.271	0.260	0.218	0.271	0.199	0.260	2.133	0.260	8.218

Table A3
Normalized performance of anaerobic digester alternatives against criteria.

	Criteria	Weight	Anaerobic Digester Alternative										
			Fixed dome	Floating drum	Agam fixed dome	LGM	EZ	DIY Biobag	Puxin	AGET	Geomembrane	STANDARD	Greenbox
Scenario 1	C-1	0.232	0.070	0.000	0.232	0.151	0.151	0.209	0.186	0.116	0.000	0.000	0.070
	C-2	0.206	0.124	0.155	0.124	0.124	0.124	0.206	0.134	0.103	0.165	0.134	0.021
	C-3	0.199	0.100	0.139	0.199	0.119	0.179	0.179	0.159	0.129	0.139	0.149	0.080
	C-4	0.078	0.055	0.016	0.051	0.047	0.047	0.047	0.055	0.047	0.062	0.008	0.066
	C-5	0.122	0.098	0.098	0.098	0.104	0.085	0.098	0.122	0.104	0.098	0.073	0.098
	C-6	0.050	0.025	0.025	0.005	0.025	0.005	0.025	0.025	0.025	0.015	0.033	0.035
	C-7	0.028	0.003	0.003	0.006	0.003	0.006	0.003	0.011	0.003	0.008	0.017	0.022
	C-8	0.084	0.055	0.008	0.059	0.067	0.067	0.055	0.063	0.055	0.017	0.017	0.000
	Overall score		***0.527***	***0.443***	***0.772***	***0.639***	***0.664***	***0.821***	***0.755***	***0.581***	***0.504***	***0.430***	***0.391***
	Rank		***7***	***9***	***2***	***5***	***4***	***1***	***3***	***6***	***8***	***10***	***11***
Scenario 2	C-1	0.166	0.050	0.000	0.166	0.108	0.108	0.149	0.133	0.083	0.000	0.000	0.050
	C-2	0.108	0.065	0.081	0.065	0.065	0.065	0.108	0.070	0.054	0.086	0.070	0.011
	C-3	0.068	0.034	0.048	0.068	0.041	0.061	0.061	0.054	0.041	0.048	0.051	0.027
	C-4	0.260	0.182	0.052	0.169	0.156	0.156	0.156	0.182	0.156	0.208	0.026	0.221
	C-5	0.044	0.035	0.035	0.035	0.037	0.031	0.035	0.044	0.037	0.035	0.026	0.035
	C-6	0.068	0.034	0.034	0.014	0.034	0.014	0.034	0.034	0.034	0.020	0.044	0.048
	C-7	0.028	0.003	0.003	0.006	0.003	0.006	0.003	0.011	0.003	0.008	0.017	0.022
	C-8	0.260	0.156	0.026	0.182	0.143	0.143	0.156	0.208	0.156	0.052	0.052	0.000
	Overall score		***0.559***	***0.279***	***0.704***	***0.587***	***0.583***	***0.703***	***0.737***	***0.564***	***0.458***	***0.287***	***0.414***
	Rank		***7***	***11***	***2***	***4***	***5***	***3***	***1***	***6***	***8***	***10***	***9***

Table A4
Overall score of digester alternative for Scenario 1 sensitivity analysis cases.

	Anaerobic Digester Alternatives										
	Fixed dome	Floating drum	Agam fixed dome	LGM	EZ	DIY Biobag	Puxin	AGET	Geomembrane	STANDARD	Greenbox
Case 0	0.527	0.443	0.772	0.639	0.664	0.821	0.755	0.581	0.504	0.430	0.391
Case 1	0.519	0.394	0.631	0.588	0.569	0.681	0.700	0.544	0.488	0.444	0.494
Case 2	0.507	0.343	0.635	0.585	0.564	0.635	0.707	0.550	0.443	0.414	0.550
Case 3	0.600	0.750	0.600	0.600	0.600	1.000	0.650	0.500	0.800	0.650	0.100
Case 4	0.553	0.546	0.618	0.593	0.582	0.818	0.678	0.525	0.621	0.532	0.325
Case 5	0.550	0.350	0.790	0.650	0.710	0.810	0.740	0.580	0.500	0.340	0.330

Table A5
Overall score of digester alternative for Scenario 2 sensitivity analysis cases.

	Anaerobic Digester Alternatives										
	Fixed dome	Floating drum	Agam fixed dome	LGM	EZ	DIY Biobag	Puxin	AGET	Geomembrane	STANDARD	Greenbox
Case 0	0.559	0.279	0.704	0.587	0.583	0.703	0.737	0.564	0.458	0.287	0.414
Case 1	0.513	0.394	0.644	0.556	0.550	0.675	0.706	0.531	0.488	0.444	0.494
Case 2	0.500	0.343	0.650	0.550	0.543	0.628	0.714	0.536	0.443	0.414	0.550
Case 3	0.600	0.750	0.600	0.600	0.600	1.000	0.650	0.500	0.800	0.650	0.100
Case 4	0.550	0.546	0.625	0.575	0.571	0.814	0.682	0.518	0.621	0.532	0.325
Case 5	0.540	0.350	0.790	0.600	0.660	0.800	0.750	0.560	0.500	0.340	0.330

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