APPENDIX OF

A multi-criteria approach for assessing the sustainability of small-scale cooking and sanitation technologies

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PRELIMINARY REMARK

The present appendix supplements a manuscript about an integrated and participatory tool called Multi-Criteria Technology Assessment (MCTA), which has been developed for assessing the sustainability of small-scale cooking and sanitation technologies. The appendix provides further details and information on the main method (Section A.1), activities performed and the computational work applied when designing the assessment method and tool (Section A.2), as well as on the process of pre-testing the tool (Section A.3). Mathematical equations are provided in Section A.4. A list of all criteria used in the assessment is provided at the end of the present appendix in Table A.8. All references used are listed in Section A.5; all non-standard abbreviations used are listed in Section A.6.

Another document called "Supplements" provides more graphs visualizing results, in addition to those presented in the main article, and tables with plot data for all graphical visualizations presented in the main article and in the Supplements.

Please contact Ariane Krause [krause@ztg.tu-berlin.de] for further information, data, or spreadsheets.

A.1. MULTI-CRITERIA DECISION ANALYSIS METHOD

The tool we proposed, the MCTA, is based on the method Multi-Criteria Decision Analysis (MCDA). In addition to the theoretical background to the MCDA method that is provided in the main article, Table A.1 summarizes the fundamental terms that are commonly used in MCDA.

Table A.1: Common terminology applied in multi criteria (decision) analysis [Dodgson et al., 2009; Gerber et al., 2012]

	Definition	Supporting question	Synonyms
Stakeholders	Actors, who have a 'stake', e.g. having an interest, being affected, or participating by any other means in the decision or implementation process.	Who makes the decision or who is affected by the decision?	Involved or affected people
Objective	Desirable purpose that shall be achieved.	What do we want to achieve? Why do we want to make a certain decision?	Goal
Alternative	A set of optional means to reach the objective that related to a choice between two or more possibilities. Alternatives usually show different consequences in terms of certain relevant criteria.	How do we want to achieve the objective? What are the alternatives that we have and that we have to choose between?	Option or scenario
Criterion (singular), criteria (plural)	Criteria constitute the practical bases for comparing alternatives and thus for decision-making; a standard by which alternatives can be compared and judged.	Which are the relevant aspects to compare the alternatives? How to make the decision?	Attributes or objectives, respectively, on a lower or higher level of the applied criteria; dimension for a group of criteria.
Weighting	Assigning subjective preferences to criteria.	What is the relative importance of a certain criterion compared to the other criteria?	Preferences
Description	Unit of information that is used to describe the performance of an alternative for a certain criterion. Indicators enable comparing the alternatives through judging.	How do criteria vary among alternatives?	Indicator
Scoring	Assigning a subjective value to the informative indicators.	What is the value of a certain performance of an alternative for a certain criterion?	Valuation (of the performance)
Index	A pointer that indicates the final overall ranking of the alternatives. The final result after any aggregation of the weighted scores.	How do the alternatives overall perform?	Overall performance

A.2. PROCESS OF DESIGNING THE SUSTAINABILITY ASSESSMENT METHOD

Overall, developing and conducting the MCTA was a dynamic process which lasted from 2012 until 2016. Conceptually designing, planning, and performing the MCTA included several activities for the planner and facilitator as well as for participants who represent several different stakeholder groups. Table A.1 summarizes the whole procedure of planning and conducting the MCTA in 9 steps, referred to alphabetically from A to G, alongside activities performed by the planner and participant involvement. Further information about certain steps is provided in following sections.

Table A.2: Steps for planning and conducting the MCTA including activities of the planner and involvement of participants, indicated along the timeline of the present study.

	Activity of the planner	Involvement of participants	Timeline
A	Framing the context of the assessment: • Participating in projects, • Short- and long-term stays in Karagwe, • Working in a team with project workers, • Reading project reports, governmental reports, and non-governmental reports, • Talking with scientists and practitioners in the region, etc. Based on the information collected, describing and defining the decision that shall be supported followed, which included: • Formulating the decision problem, the driving forces, and the motivations behind the project; • Creating process flow diagrams for better illustration of the project context.	Cooperating through sharing knowledge, experiences, thoughts, challenges, doubts, wishes, etc.	2010-2013
B	Creating alternatives Decision to conduct MCTA for discrete technology alternatives that are defined based on the case study projects.	None.	Mar. 2016
C	Selecting criteria: • Interviews with academic professionals, • Investigating practical experiences and practitioners' perspectives, • Moderated group discussions in workshops based on 'world café method', • Exhaustive literature review.	Cooperating through sharing knowledge, experiences, thoughts, challenges, doubts, wishes, etc.	2013-2015
D	Collecting data: • Field experiment • Material flow analysis • Soil nutrient balancing • Project reports, communication, cooperation • Literature and internet review.	Cooperating through sharing reports, data, 'expert' judgements, etc.	2012-2015
E	Analysing stakeholders and selecting participants:		2013-2015
	• Stakeholder analysis	Commitment to participate throughout the whole MCTA-process.	Mar. 2015
	• Decision for inviting representatives of all partners of the case study projects to participate.		
F	Preparing method and assessment tool; set-up with spreadsheets.	None.	Mar.-May 2016
G	Applying the MCTA in a 9-step-approach:	Applying the MCTA in a 9-step-approach:	
	1. *Presenting*: Preparing presentations as PDF-documents.	1. *Presenting*: Reading presentation.	Apr. 2016
	2. *Agreeing:* Preparing presentations and formulating draft version of the definition of 'driving forces' and 'motivations'.	2. *Agreeing:* Reading presentation and comment, agree, or disagree on pre-formulated definitions of 'driving forces' and 'motivations'.	Apr. 2016
	3. *Self-assessment:* Preparing and evaluating sheet for self-assessment of participants.	3. *Self-assessment:* Disclosing their role as stakeholder.	Apr. 2016
	4. *Weighting:* Preparing methods and tools for (i) ranking and rating of main-criteria and (ii) simple rating of sub-criteria through assigning numeric weights to each criterion.	4. *Weighting:* Expressing perceived importance of criteria in prepared spreadsheets.	Apr. 2016
	5. *Knowledge-exchange*: Preparing presentation with results of prior research	5. *Knowledge-exchange*: Reading presentation.	Jun. 2016
	6. *Scoring:* Formulating descriptions and preparing tool for scoring.	6. *Scoring*: Assigning numeric scores to indicate the perceived value of alternatives.	Jul. 2016
	7. *Calculating*: (i) Calculating weighted scores of all sub- and main-criteria, (ii) deducing aggregated overall results, and (iii) visualizing results.	7. *Calculating*: None.	Aug. 2016
		8. *Conclusion*: Reading presentation.	Oct. 2016
	8. *Conclusion:* Preparing final presentation for sharing results of MCTA with all participants.	9. *Evaluation*: Answering questionnaire to provide feedback and criticism, and to formulate lessons learned.	Nov. 2016
	9. *Evaluation:* Preparing questionnaire for feedback; evaluating and visualizing evaluation.		

(A) Framing the context of the assessment

In addition to describing the environment of the decision by formulating *driving forces* (Table 1 main article) and *motivation* (Table 2 main article) of projects' initiators, we created two *process flow diagrams* (PFD). The PFDs (Fig. A.1 and Fig. 1 main article) served to foster a better understanding of the technologies and possible recycling approaches while interacting with people during several research steps.

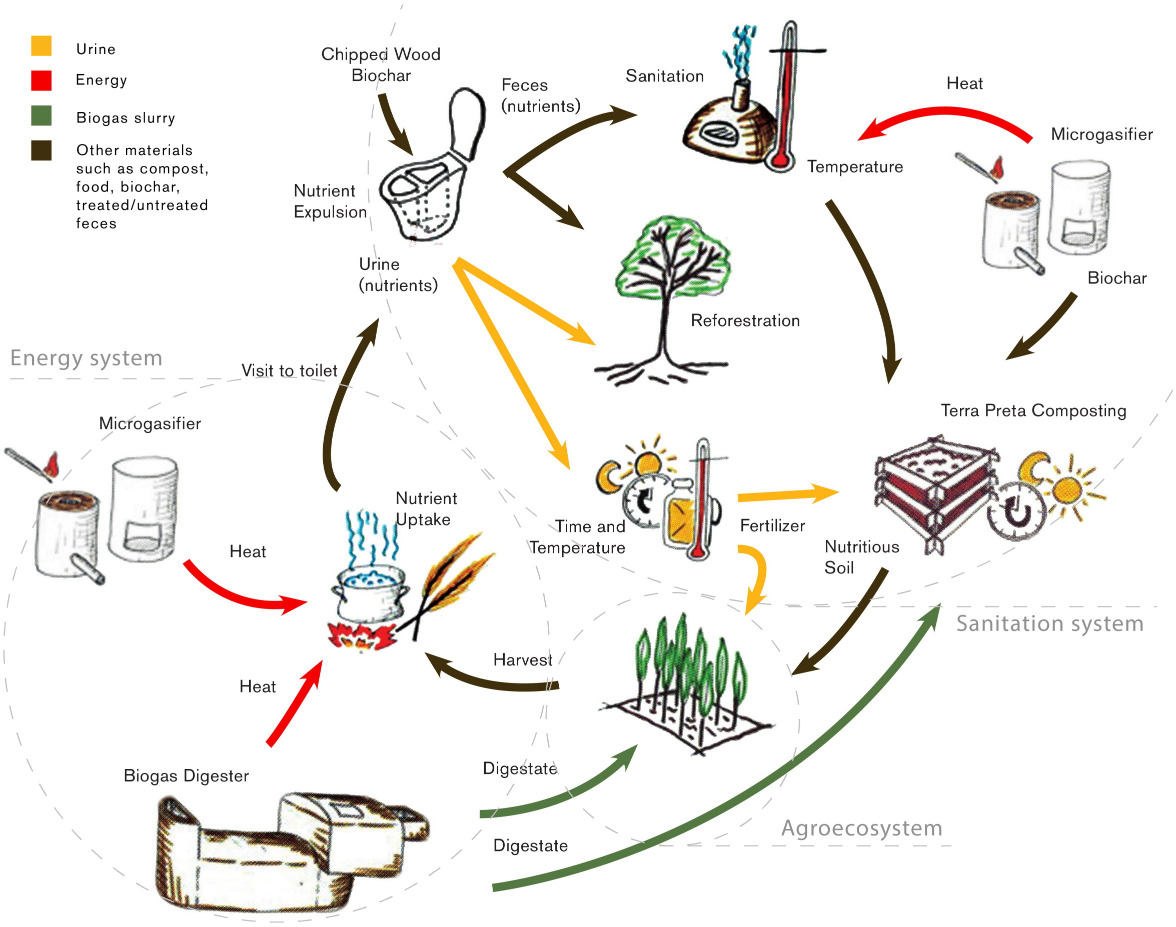


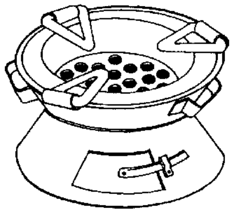
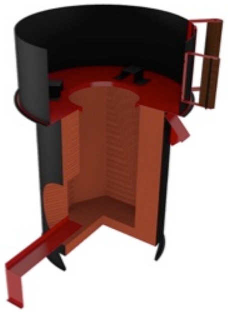
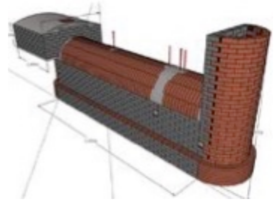
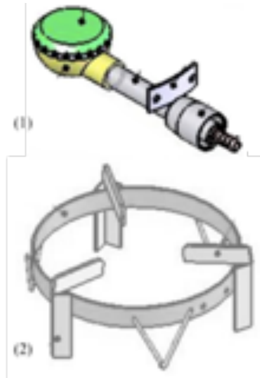
Fig. A.1: Pictorial illustration of the intersectional resource management in smallholder farming systems integrates also cooking and sanitation technologies assessed through MCTA (Krause et al., 2015)

(B) Creating alternatives

The alternatives analysed included **locally available cooking and sanitation technologies** that constitute an alternative to the current state approaches (Table 3 main article). The alternatives were *discrete* technology alternatives defined on the basis of the case study projects (Tables A.3 to A.5). The respective technologies are also the subjects of prior research (Krause and Rotter, 2017).

We also discussed options to compare different scenarios representing different strategies for sustainable community development in Karagwe with staff members of MAVUNO and CHEMA and decided on the following concept: The first scenario is a current state scenario; the second scenario describes a switch in technologies used within the energy system; the third scenario describes a switch in technologies used within the sanitation system; and the fourth scenario describes a switch in technologies used within both systems. The scenarios refer to a community of 50 households. We highly encourage future work to up-scale the MCTA to the community level and, therefore, use our results and the MCTA-tool developed.

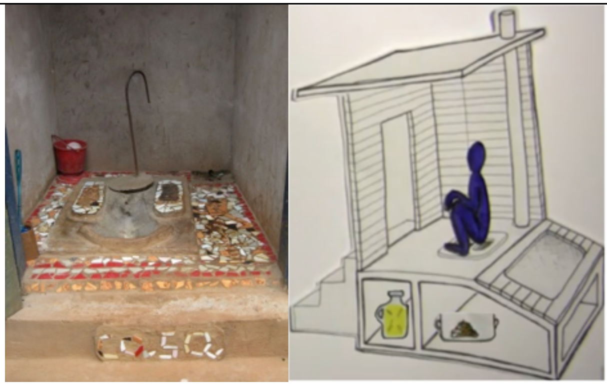
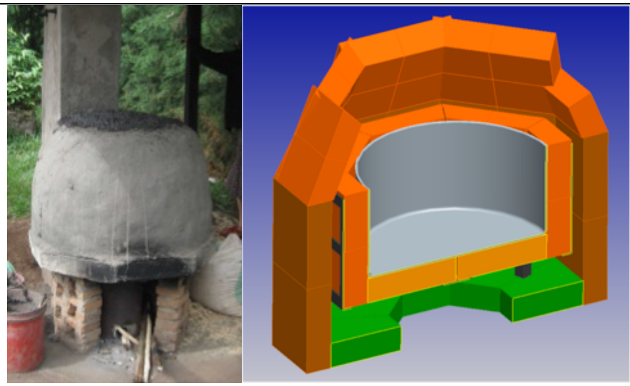
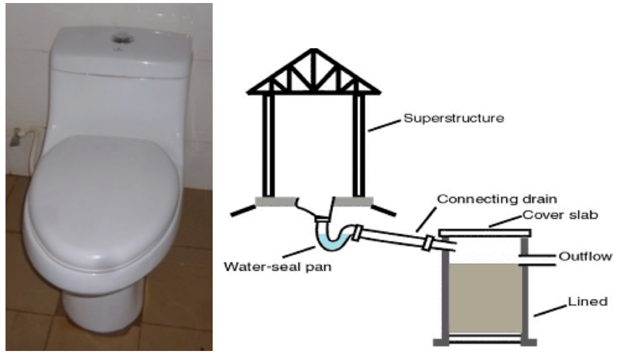
Table A.3: Pictures and short description of the analysed bioenergy alternatives that are locally available in Karagwe, Tanzania. (Table adopted from Krause and Rotter, 2017; Table A.2, Appendix A)

Charcoal burner including preceding charcoal production		Rocket stove	Microgasifier stoves including Sawdust gasifier and	Top-Lit UpDraft (TLUD)	Biogas system including biogas digester and burner	
						
						
Local charcoal producers usually work with above-ground (picture) or underground earth kilns. Distribution of charcoal through local markets and shops.	Local producers distribute at local markets and in shops..	CHEMA is the main producer and distributor in the district.	CHEMA developed the advanced sawdust gasifier in cooperation with EWB. Production at CHEMA workshop and distribution through CHEMA and on local markets.	TLUD is an open source design. CHEMA produces and distributes TLUD stoves. Another producer and distributor is Awemu Biomass Ltd. in Kampala, Uganda.	MAVUNO developed the BiogaST-digester in cooperation with EWB; the design follows the concept of a plug-flow digester.	1-combuster, 2-pot stand CAMARTEC is producer and distributor of biogas burner of the design “Lotus 2”.
Production in batches	Continuous firing	Continuous firing	Firing in batches	Firing in batches	Daily feeding	Continuous firing

Non-common abbreviations: CAMARTEC: Centre for Agricultural Mechanisation and Rural Technology; CHEMA: Programme for Community Habitat Environmental Management; EWB: Engineers without borders; MAVUNO: Swahili for “harvest”, name of a farmers’ organization; MES: micro energy system; NA: not analysed; TLUD: Top-Lit UpDraft

Charcoal production: Msuya et al. (2011), Lehmann and Joseph (2009); Charcoal burner: http://www.solutions-site.org/images/cs/cat2_sol60_charcoal-stoves.jpg, http://www.nzdl.org/gsdl/collect/fnl2.2/archives/HASH4652.dir/p18b.gif;
Microgasifier stoves: http://www.ingenieure-ohne-grenzen.org/de/Regionalgruppen/Berlin/Projekte/Effizientes-Kochen-in-Tansania-EfKoiTa; photographs by D. Fröhlich;
Biogas digester: http://www.ingenieure-ohne-grenzen.org/de/Projekte/TZA-IOG26/BiogaST-Biogas-Support-for-Tanzania/BiogaST-Forschung-und-Entwicklung-2008-2014; Biogas burner: Schrecker (2014)

Table A.4: Pictures and short description of the analysed sanitation alternatives that are locally available in Karagwe, Tanzania. (Table adopted from Krause and Rotter, 2017; Table B.2, Appendix B)

<table>
<tr><th>EcoSan
UDDT only</th><th>CaSa
UDDT and sanitation oven</th><th>WC + ST
Water toilet (Closet) and Septic Tank</th></tr>
<tr><td></td><td></td><td>
</td></tr>
<tr><td colspan="2">The UDDT is used for the separate collection and storage of urine and faeces. Toilets can be designed for sitting or squatting. After defecation, so-called “dry material” is added to enhance the drying of faeces and to reduce smells. Receptacles for collection of excreta are placed in the substructure under the toilet slab. Wastewater from anal cleansing is directed to a soil filter, which can be designed, for example, as a flowerbed.</td><td>Toilets are available for sitting or squatting. Flush water is used to transport toilet waste from WC into ST. Part of the grey water is disposed into the system, too.</td></tr>
<tr><td>Solids are collected in a chamber and primarily composted inside the toilet until the chamber is full (i.e. several weeks to months). Subsequently, it can be used in the shamba[1], e.g. by putting the matter on a rotation basis into a planting hole for a tree or cutting of a banana plant. This practice is locally called omushote.</td><td>Solids are collected in pots. If full, the pot is transported (with handles or a trolley) into a loam oven. Here, the matter is thermally sanitised via pasteurisation to inactivate pathogens that may be present in faeces. The loam oven is fired with a microgasifier. Afterwards, solids are composted with biochar (i.e. residues from sanitation process and/or cooking) and other organic residues, in accordance with the procedure as tested within CaSa-project. This compost can be used in the msiri[2].</td><td>The septic tank is an accumulation system. The solid phase settles and remains in the pit whilst the liquid fraction is leached into the surrounding soil. A septic tank can be constructed out of plastic, built with concrete or bricks, or simply consists of an unlined pit comparable to the pit of the pit latrine. The latter is dominant in Karagwe as it has the lowest construction costs.</td></tr>
</table>

Non-common abbreviations: CaSa-project “Carbonization and Sanitation”; EcoSan: ecological sanitation; UDDT: urine-diverting dry toilet.
EcoSan: http://www.ingenieure-ohne-grenzen.org/de/content/download/23394/134705/file/How%20to%20build%20a%20UDDT%20–%20Construction%20Manual%20–%20English.pdf; photographs by A. Krause;
CaSa: http://www.ingenieure-ohne-grenzen.org/de/content/download/23393/134699/file/How%20to%20build%20an%20oven%20–%20Construction%20Manual%20–%20english.pdf; photographs by A. Krause;
Septic system: http://www.unep.or.jp/ietc/Publications/TechPublications/TechPub-15/2-4/4-1-3.asp; photographs by A. Bitakwate.

[1] *Shamba* is the local name for perennial, mostly banana-based cropping systems.
[2] *Msiri* is the local name for the intercropping of temporary crops including maize, beans, and vegetables.

Table A.5: Costs and a short description of the potential access and funding opportunities for cooking and sanitation alternatives analysed. (Information based on expert judgements and project documents.)

	Costs	Access	Funding
Cooking alternatives assessed			
Charcoal burner	Selling price: 5,000-40,000 TZS ≈ 2-16 €	Purchasing on local market	From cash income or possibly with micro loan from community members or local NGO
Rocket stove	Selling price: 34,000 TZS ≈ 14 €	Purchasing at CHEMA, from local markets and shops, or through sales-person travelling to the villages.	From cash income; possibly with micro loan from community members or local NGO
Sawdust gasifier	Selling price: 31,000 TZS ≈ 12.50 €	Purchasing at CHEMA, from local markets and shops, or through sales-person travelling to the villages; initiating the implementation is funded by an external donor including staff loans and purchasing the material to construct 100 stoves; income from selling these stove will serve as capital to return construction material to the stock.	From cash income; possibly with micro loan from community members or local NGO
Microgasifier	Selling price: 29,000 TZS ≈ 12 €		From cash income; possibly with micro loan from community members or local NGO
Biogas digester	Material and labour cost: approximately 3,000,000 TZS ≈ 1,200 €	Receivable through donation with own contribution from cooperation of MAVUNO and Engineers without borders Germany	Funding through external donor for 2016: 8 digesters for 2017: 12 digesters (funding not yet agreed)"
Biogas burner	Selling price: 60,000 TZS ≈ 24 €		
Sanitation alternatives assessed			
UDDT	Material cost: approximately 450,000 TZS ≈180 € Labour costs: approximately 500,000 TZS ≈200 €	Self-made, local fundi, MAVUNO fundis	From cash income or possibly with micro loan from community members or local NGO; possibly receivable through MAVUNO and a donor project (*no defined plans yet*); community-run sanitation oven is possible but needs to be planned and organised
CaSa-oven	Material cost: approximately 630,000 TZS ≈250 € Labour costs: approximately 500,000 TZS ≈200 €	Self-made, local fundi, MAVUNO fundis	From cash income or possibly with micro loan from community members or local NGO; possibly receivable through MAVUNO and a donor project (*no defined plans yet*); community-run sanitation oven is possible but needs to be planned and organised
Septic system	Material and labour costs: 1,600,000-2,000,000 TZS ≈640-800 €	Local fundi; requires possession of a watertank	From cash income or possibly with micro loan from community members or local NGO

Non-common abbreviations: CaSa-project "Carbonization and Sanitation"; €: Euro; NGO: non-governmental organisation; TZS: Tanzanian Shilling; UDDT: urine-diverting dry toilet.

(C) Selecting criteria

In order to identify appropriate and feasible criteria to measure sustainability, I conducted **personal interviews with scientists and practitioners** in Tanzania and Uganda during December 2013 and March 2014. The main objective of the interviews was to deduce relevant criteria. Moreover, I intended to get a deeper impression of the general attitude of particularly East-African scientists on the technologies analysed as well as on the approach to recover residues for consecutive use in agriculture (Fig. A.1). Interviews were designed as semi-structured interviews. When conducting an interview, I usually started by introducing myself as well as the specific approach that my research focuses on. For the latter I utilized prepared PFDs. Based on the start of the conversation after presenting the PFDs and on the specific professional focus of the interviewee, we continued with an open discussion. Therefore, I prepared a set of topics that I intended to discuss with a certain person along with questions that I wanted to ask.

I interviewed **researchers from different scientific fields** related to the alternatives assessed including:

- Dr. H. Rajabu[3], senior researcher and lecturer for energy systems and power engineering with expertise in microgasifier cooking stoves and pyrolysis technologies;
- Dr. S. Mbuligwe[4], senior researcher and lecturer with professional experiences in public health and environmental protection including sanitation;
- Dr. P. Mtakwa[5], senior researcher with expertise in soil fertility management;
- B. Kiwovele[6], researcher and coordinator of the Southern Highland zone and lecturer for fertilization strategies particularly for small-holder farming;
- C. Lohri[7], assistant researcher of Dr. H. Rajabu with expertise in biogas and carbonization technologies applied in East-African countries;
- M. Abbo[8], managing director with expertise in analysing energy systems and testing cooking stoves,
- A. Naluwagga[6], coordinator of the regional stove testing and knowledge centre;
- K. Bechtel[6], head of bioenergy department with expertise in analysing energy systems and testing cooking stoves;
- N. Byanyima[6], bioenergy technician with expertise in testing cooking stoves;
- W. Getkate[6], management advisor with expertise in analysing energy systems and testing cooking stoves;
- F. Ogwang[9], assistant lecturer with experiences in the co-composting of human excreta for soil fertility improvement;
- Dr. J. Karungi[10], associate professor with expertise in integrated pest management.

3 Department of Mechanical and Industrial Engineering, College of Engineering and Technology, University of Dar es Salaam, Tanzania (TZ).

4 School of Environmental Science and Technology, Ardhi University, Dar es Salaam, TZ.

5 Department of Soil Science, Sokoine University of Agriculture, Morogoro, TZ.

6 Agricultural Research Institute of the Ministry of Agriculture, Food, and Cooperatives, Uyole, TZ.

7 Swiss Federal Institute of Aquatic Science and Technology (Eawag), Department of Sanitation, Water and Solid Waste for Development (Sandec), Dübendorf, Switzerland.

8 Centre for Research in Energy and Energy Conservation (CREEC), College of Engineering, Design, Art and Technology, Makerere University, Kampala, Uganda.

9 Department of Agricultural Production, Makerere University, Kampala, Uganda.

10 School of Agricultural Science, College of Agriculture and Environmental Sciences, Makerere University, Kampala, Uganda.

In addition, I received **individual consulting and coaching** by Dr. L. Scholten[11], a tenure track assistant professor with professional experiences in decision analysis and multi-criteria decision support methods. She assisted me to review and revise a pre-selection of criteria collected pursuant to applicability and relevance.

I**nterviews with practitioners** followed the same objectives as interviews with scientists, which were learning about practitioners' perspective on technologies analysed and deducing criteria that they perceive as relevant. I was, likewise, prepared with a set of topics that I intended to discuss and questions that I wanted to ask. During December 2013 and March 2014, I had the chance to interview the following practitioners:

- F. Mwitumba[12], regional coordinator of the Tanzania Domestic Biogas Program (TDBP) with experience in implementing and monitoring biogas projects in TZ with a focus on small-scale dome-biogas technologies;
- E. Kasumba[10], technical training officer of the TDBP, with experience implementing and monitoring biogas projects in TZ with focus on small-scale dome-biogas technologies;
- L. Shila[13], national programme coordinator of the TDBP and board member of the Global Initiative for Productive Biogas;
- M. Athuman[11], technologist for the design, construction and dissemination of the biogas technology;
- J. Mmbaga[11], from the bio-slurry extension office;
- N Fute[11], department of private sector development.
- N. Muhumuzwa[14], coordinator with expertise in the development and dissemination of microgasifier stoves;
- A. Musisi[15], managing director with experience in briquetting agricultural residues and disseminating briquettes for use in ICSs;
- R. Lukoda[13], sales coordinator, with experience in briquetting agricultural residues and disseminating briquettes for ICSs;
- R. Kiwanuka[16], coordinator and technician with expertise in constructing and promoting energy saving stoves including mud cooking stoves and microgasifiers;
- D. Leonidas[17], environmental engineer and coordinator of a project dealing with composting urban wastes in Dar Es Salam;
- F. Tunutu[18], program advisor of technology development for carbonization of biowaste;
- M. Veen[19], sector leader and senior advisor of renewable energy development projects in TZ.

11 Section Sanitary Engineering and section Integral Design and Management, Department of water management, faculty of Civil Engineering and Geosciences, University of Technology, Delft, the Netherlands.

12 Caritas Development Office, national implementing partner of the TDBP, Roman Catholic Church Mbeya Region, TZ.

13 Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC), national implementation agency of the TDBP, Arusha, TZ.

14 Awamu Biomass Energy Limited, Kampala, Uganda.

15 Jellitone Suppliers Ltd., Kampala, Uganda.

16 Joint energy and Environment Projects, Kampala, Uganda.

17 Bremen Overseas Research and Development Association, Dar Es Salaam, TZ.

18 Norges Vel East adn Southern Africa, Dar Es Salaam, TZ.

19 SNV Netherland Development Organiszation, Arusha, TZ.

In addition to interviews and individual discussions, I also facilitated **group discussions as part of workshops**. Participants of the workshops included:

- A group of my fellow PhD-students from the research group[20], in addition to discussing possible criteria, we also discussed the general applicability of the MCDA in the given context and possible means to adopt the method to make it more appropriate; conducted in May 2013;
- A group of sixteen senior and junior researchers including academic professionals engaged in the field of bioenergy technologies as well as representatives of the research and publication departments from the University of Mbeya[21], conducted in December 2013;
- A group of staff members form local NGOs representing the local community; participants in this group overlap participants of the MCTA; conducted at MAVUNO office, in March 2015.

All group discussions are conceptualized according to the **world café method** (Brown, 2002):

1. I start by introducing my personal background, the research site, the associated projects, and the partner organizations.
2. I present cooking and sanitation technologies and their integration into smallholder farming systems using PFDs.
3. Participants of the group discussion can ask questions in order to clarify common understanding.
4. The group is split into smaller groups, which then gather at their own table. Tables are prepared with a large, blank sheet of paper indicating one or two of the six main criteria in the centre. The task for the small groups is, to have a conversation about issues that they consider important related to the respective criteria of that table and with regard to the technologies. The objective was, to collect sub-criteria that they consider relevant to be respected in MCTA by recording them on the poster sheet.
5. After 10-15 minutes, participants rotate to go to another table whereby small groups can mix.
6. This world café terminates after each person has been at each poster table once.
7. One person of each table presents the poster from the respective table to the plenary by summarizing notes collected during world café.
8. If necessary, we discuss certain topics further with the whole group.

Finally, I also had the chance to present and discuss my approach and pre-selected criteria with a group of other PhD students participating in the workshop 'Multi-criteria Decision Analysis' facilitated by Dr. L. Scholten. This workshop was part of an interdisciplinary PhD training week[22] that I attended in Dar Es Salaam/TZ in March 2015.

The chosen main-criteria are summarized and visualized in the six-pointed sustainability star (Fig. 2 main article). In order to **make main-criteria tangible for participants**, specific guiding questions were formulated and communicated with participants during the first step of the MCTA application. These questions are as follows:

- Is the technology **reliable** from the operational-and technological perspective? For example:
  - Does the technology work in a way that is stable and durable?
  - What is needed for sound operation?

20 Microenergy systems Research Group, Postgraduate program at Center for Technology and Society, TU Berlin, Germany.

21 Department of Mechanical Engineering, Mbeya University of Science and Technology, Mbeya, TZ.

22 "Is small sustainable? Decentralizing Infrastructures and Utility Systems in East Africa", PhD summerschool of TU Berlin and TU Darmstadt, Kurasini Training & Conference Centre, Dar es Salaam, TZ.

- Is the technology **acceptable** from the environmental, socio-cultural, health and hygiene, as well as political and legal perspectives? For example:
  - Does the community accept the technology?
  - Are the environmental impacts associated with the technology acceptable?
  - Is the technology acceptable in the given cultural context?
  - Is the technology acceptable in terms of laws and legislation?
- Is the technology **affordable** from the socio-economic and financial perspectives? For example:
  - Is the technology affordable for private people or households?
  - Is the technology affordable with (micro-) loans, or covered through subsidies, or possibly financed through international development funds?
  - Is it possible to generate income with the technology?

Then, we **selected sub-criteria** based on the works of Kubanza (2016), Lohri (2012), Mucunguzi (2001), and Rajabu (2013) (Table A.6), which we applied to assess cooking and sanitation technologies (Table A.7).

Table A.6: Scientific literature that contributed most to the chosen set of criteria as well as to the applied approach of MCTA

Name of the author	C. Lohri	Dr. H. Rajabu	D. Mucunguzi	S. Kubanza
Year of publication	2012	2013	2011	2016
Title of the work	Feasibility Assessment Tool for Urban Anaerobic Digestion in Developing Countries	Improved Cook Stoves (ICS) assessment and testing	Sustainability Assessment of Ecological Sanitation Systems	Some happy, others sad: Exploring environmental justice in solid waste management
Regional context	Bahir Dar, Ethiopia	Tanzania	Kabale, Uganda	Kinshasa, Democratic Republic of Congo
Content	Participatory approach for multi-criteria assessment from sustainability perspective; based on ISWM framework; spreadsheet-based tool.	Assessment of cooking stoves that are available and most prominent in Tanzania by using a simple approach to MCA.	Multi-criteria analysis decision making framework and case study of an EcoSan-project in neighbouring Uganda.	Adopting the cultural theory framework for solid waste management by applying a multi-criteria approach

Table A.7: Numbers of the final set of sub-criteria dispersed to the six main-criteria applied for assessing sanitation and energy technologies

	total	Sanitation technologies	Energy technologies
1) Technological-operational	26	25	26
2) Environmental	17	16	17
3) Health & Hygiene	8	4	5
4) Socio-cultural	14	13	13
5) Political and legal	5	5	5
6) Socio-economic and financial	14	12	14
Sum of criteria	84	75	80

A list of all sub-criteria applied in the MCTA is provided in Table A.9 at the end of the present appendix.

(D) Collecting data

Results of prior studies are integrated within the MCTA including:

- A **field experiment**, accompanied by laboratory analysis of locally available substrates. In the experiment, substrates were used as a soil amender to evaluate the effect (i) on the crop yields that are possible to reach and (ii) on changes in the soil quality. Results of this work served to estimate possible yields depending on the potential to recover resources from cooking and sanitation technologies for fertilization (Krause et al., 2015; Krause et al., 2016)
- A **material flow analysis** (MFA) to identify and quantify technology specific flows of resources, residues, and emissions. Results served as input data for the MCTA concerning a households' estimated recycling potentials for nutrients and carbon as well as for environmental emissions such as greenhouse gases (GHGs) and nutrient leaching (Krause and Rotter, 2017).
- A combination of MFA with **soil nutrient balancing** (SNB) to integrate resources recovered from cooking and sanitation into on-farm plant nutrient management. Results of this work served as input data for the MCTA to describe the possibilities for replacing soil nutrients and carbon (Krause and Rotter, *in progress*).

We also accessed reports and data documents of the **case study projects** and interviewed project team members on demand, if certain information was missing and an 'expert' judgement was therefore required, such as prices of the technologies, lists of materials, information on current implementation strategies, etc.

To research information about the political/legal dimensions, we searched for laws, legislation, programs, etc. related to the technologies analysed in **literature and online**. Results are somewhat restricted (i) by availability of the documents specifically for Karagwe, (ii) by language barriers because laws and legislations in particular are often written in Swahili, and (iii) by quality because laws and legislation were sometimes only found as draft versions on the internet but not as final versions.

(E) Selecting participants including stakeholder analysis

When choosing participants for the MCTA, the question was: "who *shall* be represented in the assessment and who *can* participate?". We ruled out the option to conduct the MCTA directly with smallholders for the reasons that we discussed in the main article.

Hence, we rather decided to conduct the MCTA with staff members of local initiatives who also represent the local community. Most of these staff members are born in Karagwe and still live there, and work on behalf of farmers. Furthermore, most of the Tanzanian participants from MAVUNO and CHEMA, the two partner organisation and facilitators of our case study projects, have all accompanied my research projects since its beginning in 2010. These participants were thus well informed which supported reaching a common understanding of the results. In addition, I invited three colleagues to participate as representatives of the scientific partner organisation *Technische Universitä*t (TU) Berlin, of a funding institution, and of the German partner in case study projects, Engineers Without Borders (EWB). In total, the group of participants included 10 people out of whom four represented MAVUNO, two represented NGO CHEMA, four represented TU Berlin, one represented EWB, and one represented a donor institution. Double representation occurred so that one person represented TU and the donor and one person represented TU and EWB.

At the beginning of the MCTA, the group comprised twelve participants. Two participants from MAVUNO, however, withdrew during the course of the MCTA. One changed employers and continued working in another region of TZ, and another had time conflicts because of too much work.

(F) Preparing methods and tool

All computational work was done with Excel®. In total, I designed three spreadsheet documents:

1. 'MCTA_weighting' comprising:
    i. One sheet to comment on the driving forces and motivation,
    ii. One sheet to indicate the individual power and interest,
    iii. One sheet to get an overview of all criteria involved in the MCTA,
    iv. Two sheets to do a so-called 'SWING' rating of the main-criteria, and
    v. Six sheets to indicate the weights of the sub-criteria, one sheet for each group of sub-criteria belonging to one main-criterion.
2. 'MCTA_scoring' comprising:
    i. One sheet with information on the data quality (including a description whether data was qualitative or quantitative, the origin of data, and the estimated certainty of the data), on the total number of criteria for each assessment of either energy or sanitation alternatives, on the literature references, and on the terminology as well as non-standard abbreviations,
    ii. One sheet for the scoring of energy technologies, and
    iii. One sheet for the scoring of sanitation technologies. To assist the scoring, I provided a supporting question and the aim of the performance (e.g. "preferably high use of locally available resources') for each sub-criterion.
3. 'MCTA_evaluation' used to do all calculations, comprising:
    i. One sheet to summarize the answers of all participants concerning their individual role, power, interest, driver, and means of intervention in each of the three case study projects;
    ii. One sheet to calculate the individual relative weights of the main-criteria applying Eq. 1-3;
    iii. Two sheets (one each for energy and sanitation) to summarize the answers of all participants with the weights that they assigned to the sub-criteria as well as the scores that they assigned to the assessed alternatives for each sub-criteria;
    iv. Two sheets for each participant (one each for energy and sanitation) comprising the per-person data for weights and scores for all alternatives to calculate the individual relative weight from the individual adapted weight as well as the weighted scores for all sub-criteria;
    v. Two sheets (one each for energy and sanitation) to summarize the evaluation of individual weighted scores per main-criteria to calculate the overall sustainability indicator and to visualize the final results in graphs.

A.3. Process of Pre-Testing the MCTA Method and Tool

The MCTA is conducted in a stepwise and participatory procedure[23] that includes nine steps that are summarized in the main article. The Table A.2 indicates activities that are performed by the planner and the specific involvement of participants in the process. Further information about certain steps is provided in following sections.

Step 1:
To introduce the MCDA method and the connection to 'sustainability assessment', I prepared a **presentation** for participants with some general information about both methods. The presentation includes, for example, aims of MCDA, definition of 'sustainability assessment', commonly used terms, limitations of MCDA, etc. In order to be transparent, I included information about preparations I did for the MCTA-application as well as further steps, which participants would be involved in during the course of MCTA. The presentation was prepared as pdf-file and shared via a file-hosting service. Hence, each participant had individual access to that document and was able to take as much time as required to read and understand the information provided. Participants could also ask questions via email when clarification was needed.

Step 2:
After the general introduction of the method, I presented pre-defined **objectives** of the projects' initiators to the participants. I asked participating stakeholders to provide me with feedback/comments and asked whether they agree with the definition or not. Based on the comments, feedback, and suggestions I received, the first draft of the definition was adapted. The consented definitions of "**driving forces**" (Table 2) and "**motivations**" (Table 3) are presented in the main text.

Step 3:
As part of the self-assessment, participants fill-out a short questionnaire (provided as a pdf-document) for a short self-assessment. The over-arching question was: '**Who are the stakeholders**[24] **and what are their roles, power**[25]**, interests**[26] **and means of intervention?**'
Participants were requested to disclose their personal estimation about (i) their role in the projects, (ii) their power in the projects, (iii) their interest in the projects, (iv) their individual drivers, and (v) their means of intervention. They were asked to provide this information for each of the three case study projects. Results are presented in Fig. S.1 in the supplements.

Step 4:
Aim of the **weighting process** is to determine the relative importance of main- and sub-criteria for participants. Weighting is done consecutively: firstly for main-criteria and secondly for sub-criteria. Weighting was done individually, so per person. To elicit individual weights for the six main-criteria,

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23 The conceptual and analytical work was supported by Dr. L. Scholten.
24 'Stakeholder' is defined as: „actors who have a stake, an interest in the issue under consideration; who are affected by it, or who -because of their position - have or could have an active or passive influence on the decision making and implementation processes".
25 'Power' is defined as: „the extent to which they (i.e. the participants) are able to persuade or coerce others into making certain a decision or following certain courses of action".
26 'Interest' is defined as: „the extent to which a certain issue is given priority".

we used 'SWING weighting' pursuant to Dodgson et al. (2009). The general aim of the **SWING-method** is **to identify** (i) the order of the criteria in terms of their importance ('ranking'), and (ii) the relative differences in the importance of criteria ('rating'). More precisely, and according to Dodgson et al. (2009), the aim of 'SWING weighting' is to find out how participants perceive the swing from 0 to 100 for one criterion compares to the swing from 0 to 100 for another criterion and to scale these relative differences for each participant.

Short summary of SWING-method application during MCTA:
A general description summarizes examples that an exemplary alternative fulfils a certain main-criterion either at the very best level (☺) or at the worst level (☹). Examples are given for all six main-criteria which are presented in a table. The table also includes possible attribute ranges. The intention is to provide an idea, some examples, and to promote initial insight about the criteria applied and about the range that exists within alternatives perform *before* the weighting process.

A second sheet is used to elicit weighting. Therefore, participants are encouraged to take into account (i) the difference between the least and most preferred optional performance of an alternative ('ranking'), and (ii) how much they care about that difference ('rating'). Tasks given to participants to do '**ranking'** are as follows:

1. Assume that in the reference alternative, all main-criteria are on their worst level. The alternative thus receives 0 points on the preference scale for all criteria.
2. Now, imagine, that you could move the performance of the alternative for only one main-criterion from the worst level to the best level, which main-criterion would you choose? By this, identify the one criterion with the highest importance to you, indicated by highest preference to swing from 0 to 100. Give the 1st rank to this criterion.
3. Repeat this thought, which combination would you choose next? Give the 2nd rank to this criterion
4. Continue with that mental experiment until the 6th rank is assigned to the last criterion.

In order to do the '**rating'**, participants are asked to assign points ranging from 0 to 100 for each of the main-criteria to reflect how important the respective criterion is to them. The most important criterion is valued at 100 points; the lower the importance of a criterion, the lower the total points it receives, which can go down to zero points if a criterion is perceived as not at all relevant. Tasks given to participants to do the '**rating'** are as follows:

5. Assign 100 points to the criterion you assigned on the 1st rank.
6. How many points do you give to criteria ranked 2nd, 3rd, etc.; for example 83, 70, 55, etc.

During SWING, participants could choose whether they want to work with prints or with spreadsheets. From the points assigned by the participants, the planner calculates the individual relative weights of the main-criteria (Eq. 1). Documents used for ranking and rating with the SWING-method are attached to the present document.

<u>**Critique**</u>: It would have been possible to follow-up and continue further with these first steps of SWING in such ways, that, for example, participants who gave extreme weights explain reasons for their judgements. Furthermore, a group discussion about differences in weighting can be encouraged in order to formulate a consensus proposal for weighting the criteria. However, our approach is not

thoroughly participatory; mainly because participants are located in Tanzania and in Germany and are, thus, geographically separated. Moderating a group discussion via Skype is difficult or is not possible due to network challenges. An advantage of the approach as it was applied is, that individual preferences can be elicited and presented in order to identify areas of consensus or dissent. By this, we also avoided a situation where one or few people dominate the final decision about the weighting whilst others restrain because, for example, they feel less responsible, engaged, and knowledgeable, etc.

After weighting the main-criteria based using the SWING method, **weighting of sub-criteria** followed, which only comprised the 'rating' of sub-criteria. We, therefore, asked participant to assign points ranging from 0 to 100 to sub-criteria depending on how important they consider criteria. Participants weighted the sub-criteria individually, each person using one spreadsheet, and successively weighted all main-criteria from technological-operational criteria to environmental criteria, etc. We did not apply the SWING-method again because this would have consumed too much of the participants time. Each main-criteria contains at minimum of four and a maximum of 26 sub-criteria. We rather built upon the previous experience of doing the SWING-method for the main-criteria.

<u>Step 5:</u>

Between weighting and scoring, I prepared another **presentation to share the summarized results of previous research** (Krause and Rotter, 2017; Krause and Rotter, *in progress*). The objectives of this step are (i) to be transparent about scientific findings from accompanying research, which are used in the description of alternatives, and (ii) to promote knowledge transfer to all participants. Information about other research, such as laboratory analyses and field experiments, were already communicated earlier in 2015 and were also published whilst the publications was shared among participants. Results from prior research were an important source of information about the performance of the technologies analysed against, in particular, ecological and agricultural criteria.

<u>Step 6:</u>

The next step is the **scoring of alternatives**, which entails revealing individual valuations of alternatives, or assessing technologies in terms of their performance against certain criteria. Participants are asked to assign points to each alternative and to each sub-criterion. Therefore, I prepared **detailed descriptions that indicate the performance of all alternatives assessed** and for all sub-criteria. The descriptions are based on quantitative and qualitative data collected. Furthermore, I commented on the description of certain sub-criteria when, in my opinion, data was not sufficiently available and further investigations were still need. In addition, I provided information about data sources and data quality (Table A.10).

Based on the descriptions provided, participants were asked to assign points in order to score alternatives. The **scoring system applied ranges from -10 points to 10 points**, with 0 describing the mediocrity of an 'acceptable' alternative with 'good' or 'ordinary' performance (Table 4 main article). Each participant received a spreadsheet document to do the scoring and thorough instructions on how to use it and how to do the scoring. For example, I recommended to first do the scoring of all cooking alternatives; and secondly do the scoring of all sanitation alternatives which could also be done on another day because scoring required much attention, concentration, and time from participants; reading all of the descriptions was especially time-consuming.

Step 7:

The n**umerical analysis** of weights and scores assigned by participants was done in Excel®. The computational work applied is described in the main article. All **calculations,** and respective equations, applied in the assessment tool are provided below in Section A.4.

Step 8:

After finishing the calculations and visualizations, we **shared the results** and initial conclusions with participants in a presentation, prepared as a pdf-document and shared via a file-hosting service.

Step 9:

Finally, participants were asked for a final contribution in order to **evaluate** the assessment process. We therefore provided a questionnaire where we also encouraged them to formulate their individual lessons learned from participating in the MCTA. The questionnaire was prepared as spreadsheet.

All documents, such as presentations shared with participants, questionnaires, and also the Excel-tool. are available. Please write an email to krause@ztg.tu-berlin.de

A.4. CALCULATIONS APPLIED AND EQUATIONS USED

Calculations within the assessment tool are based on the following equations:

Individual relative weights for main-criteria ($W_{x,i}$):

An individual participant (x) assigns a value (Y), between 0 and 100, to each of the six main-criteria (i). The 'individual relative weight' of a participant x for a single main-criterion i ($W_{x,i}$ in %) is then determined with:

$$W_{x,i} = \frac{Y_{x,i}}{\sum_{i=1}^{6} Y_{x,i}} \quad \text{and} \quad \sum_{i=1}^{6} W_{x,i} = 100\ \% \qquad \text{Eq. (A.1)}$$

Average *relative weight* and standard error for main-criteria ($\overline{W} \pm \Delta\overline{W}_i$):

The mean of 'individual relative weights' of a main-criterion for the total number of participants (n), is deduced from (n) single 'individual relative weights' and calculated with:

$$\overline{W}_i = \frac{\sum_{x=1}^{n} W_{x,i}}{n} \qquad \text{Eq. (A.2)}$$

The corresponding error is:

$$\Delta\overline{W}_i = \frac{\sigma(\overline{W}_i)}{\sqrt{n}} \qquad \text{Eq. (A.3)}$$

Individual adapted weights for sub-criteria ($z_{x,j}$):

Each participant (x) assigns a value ranging from 0 to 100 to reflect the individual weight of each sub-criteria (j) ($y_{x,j}$). The approach to determine 'individual relative weights' from a participant (x) for a sub-criterion (j) ($w_{x,j}$ in %), however, differs from calculating the comparable parameter for the main-criteria because of the following reason, which is also already explained above:

During scoring, participants are asked to give numeric scores (S) with points ranging from -10 to +10 to all sub-criteria. In addition, participants have the chance to assign an * symbol instead of a numeric score in order avoid forced judgements. Therefore, mathematics commonly applied in SAW are refined as follows:

The tool firstly starts with a query to adapt 'individual weights' for sub-criteria (z) *if* an * is assigned:

If $S_{x,j} = *$ then $z_{x,j} = 0$ else $z_{x,j} = y_{x,j}$ Eq. (A.4)

Through Eq. A.4, those sub-criteria scored with an *, are excluded from further analysis.

Individual relative weights for sub-criteria ($w_{x,j}$):

Thereafter, 'individual relative weights' of a participant (x) for a sub-criterion (j) ($w_{x,j}$) are defined for the total number of sub-criteria (m) belonging to a certain main-criteria:

$w_{x,j} = \frac{z_{x,j}}{\sum_{j=1}^{m} z_{x,i}}$ and $\sum_{i=1}^{m} w_{x,j} = 100\ \%$ Eq. (A.5)

Individual weighted scores for sub-criteria ($r_{x,j}$):

The 'individual weighted score' of a participant (x) for a sub-criterion (j) ($r_{x,j}$) is determined based on another query:

If $S_{x,j} = *$ then $r_{x,j} = NA$ else $r_{x,j} = S_{x,j} \times w_{x,j}$ Eq. (A.6)

Individual weighted scores for main-criteria ($R_{x,i}$):

From 'individual weighted scores' of all sub-criteria belonging to a certain main-criterion I, the 'individual weighted score' of a participant (x) on the level of main-criteria ($R_{x,i}$) is deduced through simple addition:

$R_{x,i} = \sum_{j=1}^{m} r_{x,j}$ Eq. (A.7)

Individual overall SI as assessment result:

Finally, the 'individual overall SI' of a participant (x) is estimated for each alternative with:

$SI_x = \sum_{i=1}^{6} R_{x,i} \times W_{x,i}$ Eq. (A.8)

Average SI as overall assessment result':

The 'overall SI' for an alternative A, as average of all participants (n), is determined with:

$SI_A = \frac{\sum_{x=1}^{n} SI_x}{n}$ Eq. (A.9)

Table A.8: List of sub-criteria used for assessing locally available cooking and sanitation alternatives. Supporting questions and aims are provided to participants in order to ease understanding of sub-criteria.

	Sub-criteria	Supporting question	Aim
	1) **Technological** and **operational** criteria ("reliability")		
	Manufacturability (e.g. availability of resources and materials for construction, of skills, of transportation, of tools, etc.)		
1. 1	Use of local material for construction	How much of the technology can be built from materials available at the site of users?	Preferably high use of locally available resources
1. 2	Use of industrial material from local markets for construction	How much of the technology can be built with industrial materials that are available on local markets?	Preferably low use of locally available industrial resources
1. 3	Use of industrial material from national markets for construction	How much of the technology can be built with industrial materials that need to be imported to Karagwe from national and international markets?	Preferably none to low use of imported, industrial resources
1. 4	Need for transportation of material	How much effort is needed for transportation of materials with a car or truck?	Preferably low effort for transportation
1. 5	Use of local labour for construction	How much skills are required that are available with local fundis?	Preferably high use of local labour
1. 6	Use of external experts for construction	How much skills are required that are not locally available so that external experts need to contribute in construction?	Preferably low use of external labour and experts
1. 7	Use of local tools for construction	How much is needed as infrastructure for the construction, e.g. local available tools, electric tools, workshop, etc.)	Preferably low effort for infrastructure
1. 8	Use of inoculation material (cow dung and water) to start-up the technology *- only for cooking alternatives*	Where are the materials available that are required to start the biogas digester?	Preferably locally, <5-10 km
	Usability (e.g. availability and accessibility of resources for sound operation; durability, flexibility, and robustness of the system)		
1. 9	Availability & accessibility of locally available resources	How much of the required matter, which is needed for sound operation, is locally available?	Preferably all materials are locally available in more than sufficient quantities; locally: on-farm, at school, etc.
1. 10	Availability & accessibility of water	How much water is available compared to the required amount of water, which is needed e.g. for dilution, pipe flushing, operation in general?	Preferably adequate
1. 11	Need for transportation of resources	How much effort is needed to access the required resources?	Preferably low effort
1. 12	Durability without maintenance	How durable is the used technology at minimum or the ability of the technology to withstand use over time without any damage or decrease in performance and without any maintenance in this period?	Preferably long lifespan of operation without any interruptions
1. 13	Durability with small maintenance	How durable is the used technology at medium or the ability of the technology to withstand use over time with only small maintenance in this period, including only repairs?	Preferably long lifespan of operation with only few interruptions
1. 14	Durability with big maintenance	How durable is the used technology at maximum or the ability of the technology to withstand use over time including medium and bigger maintenance in this period, including change of parts?	Preferably long lifespan of operation with mayor interruptions
1. 15	Robustness towards fluctuation of usage	Can the technology cope with fluctuation or external disturbances without mayor problems?	Preferably not easy to disturb sound operation; preferable possible to cope with medium fluctuations
1. 16	Robustness towards changes in feedstock/of input substrate	If the available substrate amount is scarce (i.e. only little higher than the amount required for sound operation) and seasonal or periodic variation of substrate availability is high, how does it affect the operationability of the technology?	Preferably very adaptable, thus not affect the operation at all
1. 17	Robustness towards changes in climatic conditions (temperature & rainfall)	How robust is the technology towards changes in climatic conditions e.g. change in temperature, or change in rainfall?	Preferably very adaptable, thus not affect the operation at all
1. 18	Robustness towards user abuse	How robust is the technology towards user abuse?	Preferably not easy to disturb sound operation; preferable very robust so that user abuse will not cause problems
1. 19	Need for user training (operation)	How much training (e.g. through seminars) is needed to empower users to use the technology independently and in a safe way?	Preferably less training

	Maintainability (e.g. responsibility, complexity, training, availability of material)		
1. 20	Availability of a clear maintenance strategy	Is there a clear maintenance strategy available, which includes an explicit list that states which activities have to be conducted when, how exactly and by whom?	Preferably all included
1. 21	Small maintenance	How much of maintenance can be done by the users? ("small maintenance")	Preferably most of the maintenance
1. 22	Medium maintenance	How much of maintenance is done by local workers/fundis? ("medium maintenance")	Preferably only important works, e.g. maintain plastering, repair stove
1. 23	Big maintenance	How much of maintenance needs to be done by external experts? ("big maintenance")	Preferably none, being independent from "external experts" is a pre-condition
1. 24	Need for user training (maintenance)	How much training (e.g. through seminars) is needed for knowledge transfer to the users to conduct small maintenance independently?	Preferably less training
1. 25	Materials needed for maintenance & monitoring	Where are the materials available that are required for maintenance and monitoring?	Preferably locally, <5-10 km
	Others (e.g. openness of the technology)		
1. 26	Possibility for replication	Does the technology follow an open source patent and could the technology easily be replicated, on demand?	Preferably open and transparent technology
	2) Environmental criteria: impact on environment and natural resources		
	Utilisation and use of resources (e.g. resource efficiency, renewability of resources, land-use)		
2. 1	Saving of resources - *only for cooking alternatives*	How much less fuel is used compared to the quantity of fuel used in traditional three stone fire?	Preferably high
2. 2	Use of renewable materials	How much renewable materials are used for construction of the technology?	Preferably high
2. 3	Use of chemicals and other non-renewable resources	How much non-renewable materials are used for construction of the technology?	Preferably low
2. 4	Availability of space	How much land is required for the implementation?	Preferably low
	Increase of concentrations or contamination in the environmental compartments air, soil, and water (e.g. emissions to the atmosphere, toe the aquifers (i.e. ground- and subsurface water), to the soil)		
2. 5	Greenhouse gas emissions (GHG)	How much climate relevant gases (e.g. CO_2, CH_4, N_2O, etc.) are emitted to the air (i.e. greenhouse gases, GHG)?	Preferably very acceptable because very low
2. 6	Leaching of pathogens	How much pathogens are emitted to the water?	Preferably very acceptable because very low
2. 7	Leaching of nutrients	How much nutrients (NH_4, PO_4) are emitted to the water?	Preferably very acceptable because very low
2. 8	Infiltration of pathogens	How much pathogens are emitted to the soil (i.e. to the deeper layers that plants don't reach with their roots thus in the soil but not in agricultural land)?	Preferably very acceptable because very low
2. 9	Infiltration of nutrients	How much nutrients (N, P) are emitted to the soil (i.e. to the deeper layers that plants don't reach with their roots thus in the soil but not in agricultural land)?	Preferably very acceptable because very low
2. 10	Infiltration of other pollutants	How much other pollutants (heavy metals, etc.) are emitted to the soil?	Preferably very acceptable because very low
2. 11	Dumping/burning of non-renewable construction material	At end-of-life of the technology, to which extend will the material (used for construction) be dumped or burned and consequently lead to increased concentration in any of the environmental compartments (water, soil, air)?	Preferably very acceptable because no increase
	Recycling potential (recycling of construction material as well as carbon and plant-nutrients to the soil)		
2. 12	Total amount of recycled carbon	How much Carbon (C) can be recycled to agriculture?	Preferably high, sufficient for restoring soil carbon/humus
2. 13	Total amount of recycled nitrogen	How much Nitrogen (N) can be recycled to agriculture?	Preferably high, sufficient to meet crops N demand (100% of N demand); On average, the deficit of nutrients and thus the additional demand of nitrogen is 17 kg of N on the land with a size of 0.6 ha.
2. 14	Total amount of recycled phosphorus	How much Phosphorus (P) can be recycled to agriculture?	Preferably high, sufficient to meet crops N demand (100% of N demand); On average, the deficit of nutrients and thus the additional demand of nitrogen is 1.7 kg of P on the land with a size of 0.6 ha.

2. 15	Size of field that can be amended with the residues used as fertiliser	How much land can be fertilised through the recycling of residues to agriculture?	Preferably high, sufficient to fertilise >30% of the arable land of the farming household
2. 16	Re-use and recycling of construction material	At end-of-life of the technology, how much of the material (used for construction) can be used again?	Preferably high (>80%)
	Others (e.g. additional value through prevention or treatment of waste)		
2. 17	Contribution to waste management	How much does the use of the technology contribute to avoiding/preventing or reducing existing waste flows?	Preferably high
	3) Health and **hygiene** criteria (i.e. impact on the human beings)		
	Safety (e.g. during construction, in operation, in maintenance, etc.)		
3. 1	Safe working conditions	How safe is the construction of the energy system for the workers?	Preferably low risk
3. 2	Indoor air pollution through smoke, CO and particulate matter - *only for cooking alternatives*	How safe and healthy is the operation of the energy system concerning indoor air pollution?	Preferably low risk
3. 2	Safety in operation: risk on infection to users - *only for sanitation alternatives*	How safe and healthy is the operation of the sanitation system for the users, family and household members?	Preferably low risk
3. 3	Risk of accidents, e.g. biogas leakages, etc. - *only for cooking alternatives*	How safe and healthy is the maintenance of the energy system concerning risks for the workers?	Preferably low risk
3. 3	Safety in operation/maintenance: risk on infection to immediate environment - *only for sanitation alternatives*	How safe and healthy is the operation of the sanitation system for the workers, other farmers, etc.?	Preferably low risk
3. 4	Risk of accidents, e.g. stability of the stove, hot external surfaces, etc. - *only for cooking alternatives*	How safe and healthy is the operation of the energy system concerning the risk for accidents with the stove?	Preferably low risk
3. 4	Safety in operation/maintenance: risk on infection to downstream - *only for sanitation alternatives*	How safe and healthy is the operation of the sanitation system for others because of leakages, emissions, etc. to the environment?	Preferably low risk
3. 5	During fuel preparation	How safe and healthy is the operation of the energy system concerning the risk during preparation of the fuel?	Preferably low risk
	4) Socio-cultural criteria (i.e. impact on/from the society)		
	Cultural acceptance (e.g. acceptance of the tasks, cultural appropriation)		
4. 1	Attitude towards substrate handling including preparations (cutting, mixing, etc.)	Is it culturally accepted to handle the required resources?	Preferably mainly positive, i.e. accepted and appreciated
4. 2	Attitude towards residue handling incl. post-treatment (composting, soil amendment of fertiliser, etc.)	Is it culturally accepted to handle the residues as agricultural resources?	Preferably mainly positive, i.e. accepted and appreciated
4. 3	Willingness to change behaviour in terms of resource preparation	How is the willingness of the users to change their behaviour and full-fill "new" tasks in terms of fuel preparation for cooking, e.g. collecting and separating wastes, cutting banana stem, collecting sawdust, etc. or of preparing resources for sanitation, e.g. collecting and separating ashes, collecting sawdust, etc.?	Preferably high
4. 4	Willingness to change behaviour in terms of residue use	How is the willingness of the users to change their behaviour and full-fill "new" tasks in terms of using residues from cooking such as biogas slurry as fertiliser, using biochar for composting, prepare compost, etc. or using residues from sanitation like human excreta as fertiliser, using biochar for composting, prepare compost, etc.	Preferably high
4. 5	Suitability for local food preparation - *only for cooking alternatives*	Is the technology appropriate for the local cultural tradition, e.g. preparation of local food, esp. staple food or applying anal cleansing?	Preferably very appropriate
4. 5	Suitability for local toilet culture - *only for sanitation alternatives*	Is the technology appropriate for the local cultural tradition, e.g. squatting, applying anal cleansing?	Preferably very appropriate
	Social impacts (e.g. social justice, social welfare, etc.)		
4. 6	Equal opportunity for inclusion	How equal are the opportunities for different members of the community to access the technology?	Preferably high

4. 7	Improvement of people's life quality	Does usage of the technology improve the people's life quality?	Preferably very positive
	Convenience (e.g. usability, comfort, flexibility of the system, adapted towards the users' needs, etc.)		
4. 8	Ease of operating, cleaning, etc.	How much effort is required for appropriate operation of the technology?	Preferably low
4. 9	Ease of residue handling	How much effort is required for handling the residues appropriately?	Preferably low to adequate
4. 10	Flexibility concerning fuel resources	Is a variability of resources possible, e.g.. can different materials be used for cooking/firing the oven or can different materials be used, e.g. for preparing the dry material, making compost?	Preferably possible, but not required
4. 11	Flexibility concerning the use	Is it possible to use different pots, cook different meals, different people using the toilet, etc. or to use the toilet in different ways?	Preferably possible without any changes in the technology or extra parts
4. 12	Towards user's needs	Is it possible to adapt the technology towards the needs of different users concerning age, gender, income groups, etc.?	Preferably possible to high extend
	System perception (e.g. social representation of the technology, other cultural aspects)		
4. 13	Looks and status symbol	Does the technology look good or act as status symbol?	Preferably very positive image
	5) Political and **legal** criteria (i.e. impact from the politics)		
	Legal situation (i.e. current legal acceptability)		
5. 1	Coverage by current policies	Are the current national and international policies disruptive, neutral or supportive regarding the proposed technologies?	Preferably supportive
5. 2	Coverage by current legislations, standards, and regulations.	Are the current national and international laws, standards and regulations that are relevant for the technology disruptive, neutral or supportive?	Preferably supportive
5. 3	Current law enforcement practices	Are current enforcement practices of laws disruptive for the projects (e.g. high enforcement for very strict laws/standards), neutral (e.g. medium enforcement for medium strict laws/standards) or supportive (e.g. low enforcement for strict laws/standards)?	Preferably supportive
	Legal development (i.e. future legal acceptability)		
5. 4	Prospect of establishing supportive policies regarding the technologies	Are the chances that supportive policies for the technologies will be established in the near future low, medium or high?	Preferably high
5. 5	Prospect of enacting and enforce supportive legislation, standards and regulations relevant for the technologies	Are the chances that supportive legislation, standards and regulations relevant for the technologies will be enacted and enforced in the near future low, medium or high?	Preferably high
	6) Socio-economical and **financial** criteria		
	Costs (e.g. investment, operational, and maintenance costs)		
6. 1	Costs for implementation (=investment costs/lifespan)	How much are the total costs for implementing the technology per year, thus split over the accepted lifespan of the technology ?	Preferably low Average household income is estimated between 450,000 and 900,000 TZS depending if both, man and woman are generating monetary income, or only the man or only the woman.
6. 2	Costs for operations (e.g. for fuel, transport, etc.)	How much are the annual costs for operating the technology?	Preferably low Average household income is estimated between 450,000 and 900,000 TZS depending if both, man and woman are generating monetary income, or only the man or only the woman.
6. 3	Costs for maintenance	How much are the annual costs for conducting maintenance with the technology?	Preferably very low, appropriate for households
	Affordability (through private investment or external funding)		
6. 4	Affordability and willingness as well as ability to pay	Is the technology affordable for the local community? This means, it possible to make a private investment to purchase the technology, i.e. paying with cash income or through micro loan from a community-based organisation or group?	Preferably technology is very affordable

6. 5	Funding through finance institute	If it is based on a loan, how are the conditions including payback period and interest rate?	Preferably supportive
6. 6	Funding through donors	To what extend is it possible to receive external funding from external donors (e.g. through development cooperation) for the investment in the technology?	Preferably supportive to finance what is required
6. 7	Subsidies	To what extend is it possible to receive subsidies as national support for the investment in the technology; are there financial incentives by local or regional authorities?	Preferably supportive to finance what is required
	Contributing to increase people's capacity to meet their need (e.g. through income generation, food sovereignty, etc.)		
6. 8	Direct through employment generation	To what extend is it possible to generate direct income with the technology through income generation for the implementers?	Preferably very acceptable for the community (more than 5 jobs generated compared to the current situation with fair salaries and working conditions)
6. 9	Direct through reduction of fuel use - *only for cooking alternatives*	To what extend is it possible to safe money through reduced fuel use?	Preferably high, e.g. more than 50% saving of the monthly fuel costs
6. 10	Indirect through selling of by-products	To what extend is it possible to generate income with the technology for the users through selling the by-products?	Preferably high, e.g. more than 30% of the farm income is connected with using by-products of the new technology
6. 11	Indirect through using of by-products	How is the impact of using by-products on the harvest yields and particularly on the possibility to increase farm income by selling share of the increased harvest?	Preferably increase of harvest and income by more than 300%
6. 12	Indirect benefit through using of by-products	How is the impact of using by-products on the harvest yields and particularly on the food supply of the farming household?	Preferably increase of harvest by more than 300% which leads to food security in the household
	Others (e.g. payback time, payback source)		
6. 13	Time needed to pay back the investment	How much time is needed to pay back the investment, e.g. pay back a received loan, or replace savings again, etc.?	Preferably low, e.g. less than 2 years
6. 14	Sources for paying back the investment - *only for cooking alternatives*	How much money of the investment will be paid back from benefits of the stove (e.g. fuel saving, income generation)?	Preferably low, e.g. less than 2 years

Table A.9: Information about kind of data and data sources used to estimate the certainty of data and to provide participants information / comments during scoring about data available and description provided

Sub-criteria	Crit. no.s	Kind of data	Description of data sources	Estimated certainty (1-5)	Comment
1) Technological-operational					
Manufacturability	1.1. - 1.8.	Exclusively qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions, literature (Rajabu and Ndilanha, 2013)	ok (3)	
Usability	1.9. - 1.19.	Mainly qualitative			
		Partly quantitative	Results from material flow analysis (Krause and Rotter, 2016a)	good (4)	
Maintainability	1.20. - 1.25.	Exclusively qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions, literature (Rajabu and Ndilanha, 2013)	ok (3)	
Others	1.26.	Exclusively qualitative			
2) Environmental					
Utilisation of resources	2.1. - 2.4.	Mainly quantitative	Results from material flow analysis (Krause and Rotter, 2016a)	good (4)	
		Partly qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions	ok (3)	
Increase of concentrations or contaminations	2.5. - 2.11.	Mainly quantitative	Results from material flow analysis (Krause and Rotter, 2016a), assumptions	good (4)	
Recycling potential	2.12. - 2.16.	Partly qualitative	Assumptions	ok (3)	
		Mainly quantitative	Results from material flow analysis (Krause and Rotter, 2016a)	good (4)	
Others	2.17.	Exclusively qualitative	Assumptions	ok (3)	
3) Health & Hygiene					
Safety	3.1. - 3.8.	Mainly qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions	ok (3)	
		Partly quantitative	Bachelor thesis associated to EfCoiTa-project, measuring the indoor air pollution in farming household (Randrianarisoa, 2016)	good (4)	
4) Socio-cultural					
Cultural acceptance	4.1. - 4.6.	Exclusively qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions, literature (Rajabu and Ndilanha, 2013)	poor (2)	I felt uncertain when describing this part; especially the cultural acceptance was difficult to describe for me as a European.
Social impacts	4.7. - 4.8.				
Convenience	4.9. - 4.13.				
System perception	4.14				
5) Political and legal					
Legal situation	5.1. - 5.3.	Exclusively qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions, literature (Rupf et al., 2015)	very poor (1)	I felt very uncertain when describing this part because of lack of information (laws and regulation changed during the course of my research; I found contradicting information about legislative progress; most laws and regulation are available in Swahili only, laws sometimes only as draft in the internet, little information on the legal situation was collected by partner organisations.)
Legal development	5.4. - 5.5.	Exclusively qualitative			
6) Socio-economic and financial					
Costs	6.1. - 6.3.	Mainly quantitative	Project documents (e.g. reports, surveys), expert judgements (i.e. EWB project team members), internet research	ok (3)	To 6.4.-6.12.: I felt uncertain when describing this part because of lack of information.
		Partly qualitative	Assumption	ok (3)	
Affordability	6.4. - 6.7.	Exclusively qualitative	Project documents, expert judgements (i.e. MAVUNO and CHEMA staff members, EWB project team members), assumptions	ok to poor (2-3)	
Contribution to people's needs	6.8. - 6.12.	Mainly quantitative			
		Partly qualitative	Results from field experiment in 2014 (Krause et al., 2016)	ok to poor (2-3)	
Others	6.13. - 6.14.	Exclusively qualitative	Assumption	poor (2)	

A.5. LIST OF REFERENCES

Brown J (2002) A Resource Guide for Hosting Conversations That Matter at The World Café. The World Café Community. Available at: http://www.meadowlark.co/world_cafe_resource_guide.pdf Last access: 20 Nov 16

Dodgson J S, Spackman M, Pearman A, Phillips L D (2009) Multi-criteria analysis: a manual. Communities and Local Government Publications, West Yorkshire/London, United Kindgom

Gerber J F, Rodríguez-Labajos B, Yánez I, Branco V, Roman P, ..., Johnson P (2012) Guide to multicriteria evaluation for environmental justice organisations. EJOLT Report, 8:45

Hellström D, Jeppsson U, Kärrman E (2000) A framework for systems analysis of sustainable urban water management. Environ Impact Assess 20(3), 311-321. doi:10.1016/S0195-9255(00)00043-3

Krause A, Kaupenjohann M, George E, Köppel J (2015) Nutrient recycling from sanitation and energy systems to the agroecosystem - Ecological research on case studies in Karagwe, Tanzania. Afr J Agric Res, 10(43), 4039-4052. doi:10.5897/AJAR2015.10102

Krause A, Kaupenjohann M, George E, Köppel J (2015) Nutrient recycling from sanitation and energy systems to the agroecosystem - Ecological research on case studies in Karagwe, Tanzania. Afr J Agric Res, 10(43), 4039-4052. doi:10.5897/AJAR2015.10102

Krause A, Nehls T, George E, Kaupenjohann M (2016) Organic wastes from bioenergy and ecological sanitation as a soil fertility improver: a field experiment in a tropical Andosol. SOIL, 2, 147-162. doi:10.5194/soil-2-147-2016

Krause A, Rotter V S (2017) Linking energy-sanitation-agriculture: Intersectional resource management in smallholder households in Tanzania. Sci Total Environ, 590-591, 514-530. doi:10.1016/j.scitotenv.2017.02.205

Krause A, Rotter V S (in progress) Recycling-based soil fertility management around the energy-sanitation-agriculture nexus in smallholdings in Tanzania, prepared for submission

Kubanza, N. S. (2016) Urban environmental problems: social and environmental injustices in solid waste management in Kinshasa, the Democratic Republic of Congo, Doctoral dissertation, University of the Witwatersrand, Johannesburg, South Africa

Lehmann J, Joseph S (2009) Biochar for Environmental Management - Science and Technology. Earthscan, London, Sterling. ISBN 978-1844076581

Lohri C R (2012) Feasibility Assessment Tool for Urban Anaerobic Digestion – A participatory multi-criteria assessment from sustainability perspective applied in Bahir Dar, Ethiopia. Masterthesis, Wageningen University, Swiss Federal Research Institute for Aquatic Science & Technology, Eawag, Zürich, Switzerland

Msuya N, Masanja E, Temu A K (2011) Environmental burden of charcoal production and use in Dar Es Dalaam, Tanzania, J Environ Prot, 2(10), 1364-1369. doi:10.4236/jep.2011.210158

Mucunguzi D B (2010) Sustainability assessmend of ecological sanitation using multi criteria analysis: A Case Study of Kabale, Uganda, Dissertation for the Degree of Masters, University of Dar es Salaam, Tanzania

Rajabu H M, Ndilanha A E (2013) Improved Cook Stoves Assessment and Testing. ICS Taskforce Tanzania, University of Dar Es Salaam, [Songela F, Magessa F, Veen M (Eds.)] SNV, Tanzania

UN (2016) Progress towards the Sustainable Development Goals. Report of the Secretary-General, E/2016/75, 28 pp

Van de Klundert A, Anschütz J (2001) Integrated sustainable waste management–the concept. In: Tools for Decision-makers, Experiences from the Urban Waste Expertise Programm (1995-2001), Scheinberg A (Ed.), WASTE, Gouda, The Netherlands

A.6. List of Abbreviations

CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CREEC	Centre for Research in Energy and Energy Conservation
€	Euro
EcoSan	Ecological sanitation
EWB	Engineers Without Borders
MCDA	Multi-criteria decision analysis
MCTA	Multi-criteria technology assessment
MFA	Material flow analysis
NGO	Non-governmental organisations
PFD	Process flow diagrams
PM	Performance matrix
SAW	Simple additive weighting
SCD	Sustainable community development
SI	Sustainability index
SNB	Soil nutrient balancing
TDBP	Tanzania Domestic Biogas Program
TLUD	Top-Lit UpDraft
TU	Technische Universität
TZ	Tanzania
TZS	Tanzanian Shilling
UDDT	Urine-diverting dry toilet

Abbreviations used in the equations:

m	Total number of sub-criteria
n	Total number of participants
$r_{x,j}$	Individual weighted score of a participant x for a sub-criterion j
$R_{x,i}$	Individual weighted score of a participant x for a main-criterion i
S	Numeric score given during scoring
SIA	Overall SI’ for an alternative A
SI_x	Individual overall SI’ of a participant x
$w_{x,j}$	Individual relative weight of a participant x for a single sub-criterion j
$W_{x,i}$	Individual relative weight of a participant x for a single main-criterion i
$y_{x,j}$	Value, or absolute score, assigned by participant x for weighting a single sub-criterion j
$Y_{x,i}$	Value, or absolute score, assigned by participant x for weighting a single main-criterion i