General Annex

to

Valuing wastes

An Integrated System Analysis of Bioenergy, Ecological Sanitation, and Soil Fertility Management in Smallholder Farming in Karagwe, Tanzania

vorgelegt von
Dipl.-Ing.
Ariane Krause
geb. in Freiburg i. Brsg.

von der Fakultät VI – Planen Bauen Umwelt
der Technischen Universität Berlin
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Promotionsausschuss:

Vorsitzende:	Prof. Dr. Eva Nora Paton
Gutachter:	Prof. Dr. Johann Köppel
Gutachterin:	Prof. Dr. Vera Susanne Rotter (Fak. III)
Gutachterin:	Prof. Dr. Friederike Lang (Albert-Ludwigs-Universität Freiburg)

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Chapter 2

Appendices

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APPENDIX A OF

Linking Energy-Sanitation-Agriculture: Intersectional Resource Management in Smallholder Households in Tanzania

MODELLING THE MICRO ENERGY SYSTEM (MES)

A. Krause, V. S. Rotter

Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

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PRELIMINARY REMARK

Chapter A.1 describes first the basic definitions of the MES-model (Section A.1.1.), including an introduction of the analysed technologies, and further elaborates on how the WBT data sets were used for characterizing the cooking task (Section A.1.2.). Thereafter, some basic information on the general structure of the computational work is provided (Section A.1.3.). Then, the alternatives of the assessment are presented in more detail including the underlying processes that we considered (Section A.1.4.). In addition, we also present the respective flow diagrams of the six analysed alternatives, as set up in the MFA-software we used.

In Chapter A.2, we provide more in-depth information about the modelling and explain the equations that we applied to systematically quantify relevant material flows ($\dot{m}$) in the MES including (i) the $\dot{m}$ of resources that are required as input (Section A.2.1.), (ii) the $\dot{m}$ of residues provided as output (Section A.2.2.), and (iii) the $\dot{m}$ of emissions as output to the environment (Section A.2.3.).

In Chapter A.3, we describe how we assessed the emissions to the environment to deduce their impact.

Chapter A.4 discusses some results of the data evaluation including (i) how the collected data from a standardized test was used to characterize the analysed stoves (Section A.4.1.). Likewise, we elaborate how data from the biogas case study was used to characterize the analysed biogas digester (Section A.4.2.). We further list the plausibility criteria used in the MES analysis (Section A.4.3.) and conduct the uncertainty check as part of the evaluation of the results (Section A.4.4.).

In Chapter A.5, we (i) provide information on the means of data collection and various sources from scientific theory and applied practice and (ii) list all material characteristics and other parameter values that we used for modelling the MES (Table A.12).

Finally, Chapter A.6 summarizes all flows and processes that we considered in the MES-model (Table A.13).

All references that we used in the MES-model are listed in Chapter A.7.

All non-standard abbreviations are listed in Chapter A.8.

In addition, pdf-documents are attached showing the Excel-spreadsheets with the model calculations for all of the six analysed energy alternatives.

A.1. General information

A.1.1. Definition of the system

We made basic assumptions for all alternatives analysed in the micro energy system (MES) regarding (i) the "housing system", which describes the system's boundaries, and (ii) the "cooking task", which was the main activity in the MES-system (Table A.1).

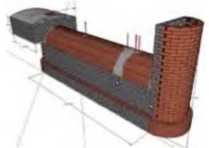
Table A.1: Basic description of the MES for all alternatives (E1-E6).

Housing system		Cooking task	Series of phases		
Number of people per family:	6				
Number of families:	1		HP_cold	HP_hot	LP
Years for modelling:	1	1^{st} cooking	1	0	1
Respective days:	365	2^{nd} cooking	0	1	2
MF [days hh^{-1} yr^{-1}]	365	SUM [number $days^{-1}$]	1	1	3

The **cooking task** characterizes the local cooking habit. In Karagwe district, in Northwest Tanzania (TZ), most farming households (hh) eat twice a day (≈ 75 % of hh; Tanzania, 2012). According to local experts, cooking typically starts with a small meal in the morning, which consists of nutritious porridge (in Swahili: *uji*) or sugary tea (*chai*). A big meal is prepared either in the afternoon or in the evening, which is most likely banana/plantain with beans (*matoke*), rice with beans (*wali maharage*) or maize porridge with beans (*ugali maharage*). Hence, the cooking task was defined as cooking two times per day with a short activity in the morning and a longer preparation of the main meal in the evening. We quantified the cooking task with ≈ 3.2 hours per day for each household, which corresponds to local routines (EfCoiTa, 2014) and literature (Vögeli et al., 2014). To transfer the material flows from a daily to an annual basis, we used the model factor (MF) in most equations.

To perform this cooking task, we compared selected, locally available energy technologies (Table A.2; with pictures). In the MES-model, we compared six alternatives that included eight technologies (also see Table 2 of the main text): the current state of using either (E1) a three-stone-fire or (E2.2) a charcoal burner, three types of improved cooking stoves (ICS) including (E3) a rocket stove, (E4) a sawdust gasifier, and (E5) a Top-Lit UpDraft (TLUD) microgasifier stove, as well as (E6.2) a biogas burner. The alternatives E2 and E6 further included the preceding processes, respectively, (E.2.1) charcoal production and (E6.1) biogas digester.

Table A.2: Pictures, description of local production, and local prices of technologies analysed in the MES-model.

E1	E2.1	E2.2	E3	E4	E5	E6.1	E6.2
Three-stone-fire 3SF	Charcoal production CP	Charcoal burner CB	Rocket stove RS	Sawdust gasifier SG	Top-Lit UpDraft microgasifier stove TLUD	Biogas digester BGD	Biogas burner BGB
							
							 1-combuster, 2-pot stand
Easily prepared on-site. Continuous firing possible.	Local charcoal producers usually work with above-ground (picture) or underground earth kilns. Distribution of charcoal through local markets and shops.	Local producers distribute on local markets and in shops..	CHEMA is 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.	CAMARTEC is producer and distributor of biogas burner of the design “Lotus 2”.
Continuous firing costs: *none*	Production in batches *NA*	Continuous firing 5,000-40,000 TZS ≈2-16 € (selling price)	Continuous firing 34,000 TZS ≈14 € (selling price)	Firing in batches 31,000 TZS ≈12.50 € (selling price)	Firing in batches 29,000 TZS ≈12 € (selling price)	Daily feeding ≈ 3,000,000 TZS ≈1,200 € (material+labour costs)	Continuous firing 60,000 TZS ≈24 € (selling price)

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; TZS: Tanzanian shilling;
Names: see Section A.1.4.
Sources:
E1: photo: http://www.lowtechmagazine.com/2014/06/thermal-efficiency-cooking-stoves.html; drawing: http://www.nzdl.org/gsdl/collect/envl/archives/HASH0165/064374a4.dir/p087a.gif; E2.1: photo: Msuya et al. (2011); drawing: Lehmann and Joseph (2009); E2.2: photo: http://www.solutions-site.org/images/cs/cat2_sol60_charcoal-stoves.jpg; drawing: http://www.nzdl.org/gsdl/collect/fnl2.2/archives/HASH4652.dir/p18b.gif;
E3-E5: photos and drawings: http://www.ingenieure-ohne-grenzen.org/de/Regionalgruppen/Berlin/Projekte/Effizientes-Kochen-in-Tansania-EfKoiTa; sketches and photographs by D. Fröhlich; E6.1: photos and drawings: http://www.ingenieure-ohne-grenzen.org/de/Projekte/TZA-IOG26/BiogaST-Biogas-Support-for-Tanzania/BiogaST-Forschung-und-Entwicklung-2008-2014; E6.2: photo and drawing: Schrecker (2014).

A.1.2. Description of the cooking task with the WBT data sets

To apply the scientific data to real life, we translated the cooking activity into a series of phases that occur in a so-called **“water boiling test”** (WBT) (Table A.1). The WBT is a simplified simulation of a cooking process for stove testing, which follows a standardized, internationally recognized and established procedure (WBT, 2014). On average, the amount of energy needed to prepare a defined type of food is independent of the kind of stove technology used. In WBT-terminology, this parameter is called “cooking energy delivered to pot”. However, as stove technologies differ in efficiency, they also differ in terms of the so-called “total energy demand”, fuel requirements, and produced emissions when performing the same cooking task. According to the **WBT-protocol** (WBT version 4.2.3, 2014), the procedure for stove testing comprises three phases: (i) heating 5 dm^3 of water on the cold stove to reach the boiling point, (ii) keeping the water around the boiling point for 45 minutes (i.e. *simmering*), and (iii) repeating the first phase with a hot stove but with fresh water, which is then again heated to reach the boiling point. As most power is required for heating water to the boiling temperature, the respective phases are termed “high power”-phase (HP). The simmering phase is called “low power”-phase (LP) because less power is needed to keep water around the boiling point. To sum up, the three phase are: (i) boiling at “high power with cold stove” (HP_cold), (ii) boiling at “high power with hot stove” (HP_hot), and (iii) simmering at LP.

Throughout the test, data is collected in a standardized and open source spreadsheet, which includes direct calculations of parameters describing the performance of the stove (e.g. efficiency, fire power, time-to-boil, fuel consumption). If appropriate equipment is available, various emissions can be measured during the WBT (e.g. CO, CO_2, and particulate matter (PM)). Parameters describing a stove’s performance are calculated both separately for each phase and as a general average for the whole test. Section A.4.1 presents a summary of the estimated means from the WBT-data, which characterise the analysed energy technologies.

A.1.3. Basic information on computational work

For the material flow analysis (MFA), we combined Excel and the MFA-software STAN[1]. We linked the data collection, data evaluation, and calculations of material flows for all alternatives in one **Excel** file comprising various **spreadsheets** (soft copies are attached to this appendix):

- Evaluation of collected WBT-data: one sheet for each stove technology and the respective data set;
- Evaluation of data collected from two digesters from the BiogaST-project (Section A.1.4) during the pilot testing in TZ in order to estimate the BiogaST-digester’s performance;
- Summary of data on various process and material values, collected from literature;
- Summary of collected values and auxiliary calculations relevant for modelling the full oxidation process (e.g. molar masses, densities, emission factors, etc.);
- Calculations of material flows of each alternative E1 to E6 in one sheet, structured in three parts:
  1. “Process values from WBT” provides relevant results from the WBT data evaluation for the respective technology (i.e. fuel consumption and emissions for the different WBT-phases).
  2. “Material and process values” comprises selected values from data collection that were required for the calculations in this sheet (e.g. moisture content, nutrient concentrations in fresh matter (FM), etc.).
  3. “Flows for STAN” calculates $\dot{m}$ of goods (G) and indicator substances [carbon (C), nitrogen (N), and phosphorus (P)]. (Note: Below, the so-called “layer” of modelling is indicated with the first index after the abbreviation of the flow, e.g. F_P means the flow of P in fuel.)
- Summary table of calculated flows for alternatives E1 to E6 for transfer to STAN via copy/paste.

In **STAN**, we reconciled the data for all flows and visualized the results as flow diagrams. Afterwards, we transferred the values to Excel again to display the results as bar diagrams.

[1] *subSTance flow ANalysis* (STAN) is a freeware developed by the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology (Cencic and Rechberger, 2008; Cencic et al., 2012).

A.1.4. General description of the analysed energy systems including flow diagrams

Before going into more detail regarding the modelling, we will shortly introduce the case studies of this work and provide an overview about the energy technologies that we analysed in the alternatives E1 to E6 (Table A.2). We further present the individual models as set up in the MFA-software we used. Thereby, all $\dot{m}$ are depicted as black arrows, processes as black boxes, and processes that contain further sub-processes as blue boxes.

We selected the alternatives based on **local conditions**, which were assessed according to the national census of agriculture in the Kagera region (Tanzania, 2012): Currently, ≈ 96 % of the households in Karagwe district use firewood as the main energy carrier and ≈ 3 % use charcoal; the remaining ≈1 % is of unspecified "other sources".

Recently, local initiatives have supported the implementation of appropriate bioenergy technologies. Thus, two of these projects act as a case study to analyse the different locally available cooking alternatives:

- The **project "Biogas Support for Tanzania"** (BiogaST) provides bioenergy for cooking through small-scale biogas digesters. MAVUNO Project, Improvement for Community Relief and Services (*mavuno,* Swahili for "harvest"), a local non-governmental organisation of organic farmers, facilitates the BiogaST-project. Cooperation partners are the Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC) in Arusha/TZ, the association Engineers Without Borders from Berlin, Germany (EWB), the University of Hohenheim in Stuttgart, Germany, and the Technische Universität (TU) Berlin, Germany.
  Initially, pilot studies were conducted in Germany (from 2009–2010) and in TZ (from 2010–2013). Thereafter, the technology was implemented and is currently tested on an institutional level (construction in 2015; operation started in the beginning of 2016) in a girls' secondary boarding school as well as on a household level (implementation started in 2016 for altogether eight families). The BiogaST-project is a case study for this analysis and (i) defines the system of a biogas burner and a biogas digester in E6 and (ii) provides data collected during the pilot operation.
- The **project "Efficient Cooking in Tanzania"** (EfCoiTa) disseminates ICS including rocket and microgasifier cooking stoves. The Programme for Community Habitat Environmental Management (CHEMA), a local initiative aiming at empowering communities through training in natural resources management and sustainable agriculture, facilitates the EfCoiTa-project. Cooperation partners are EWB Germany and the TU Berlin, Germany, as well as the Center for Research in Energy and Energy Conservation (CREEC) based at Makerere University and Awamu Biomass Energy Ltd, both located in Kampala, Uganda.
  The project started in 2012 with an evaluation of existing types of cooking stoves in the region, which led to the development of three ICSs, based on the principle of micro-gasification and adapted to the local conditions (i.e. using locally available fuels; construction with locally available material and available tools). In 2014, a series of so-called water boiling tests was performed to assess the resource efficiency and, in 2015, so-called controlled cooking tests were conducted together with kitchen performance tests to evaluate the practical use of the stoves in local households. In 2016, the current phase of the project has started focussing on the dissemination of the stoves through the local markets.
  The EfCoiTa-project is a case study for this analysis and defines the alternatives E4 and E5 whilst providing data collected during the pilot operation, especially the WBT-data sets.

Alternative E1: A three-stone-fire is a simple and cheap approach to cooking where three stones, preferably with the same height, are put together to give support to the cooking pot. The fuel is put underneath and lit to have an open fire. One big advantage of the three-stone-fire is its versatility (Grimsby et al., 2016), which means that a big variety of fuels can be utilized in this cooking method including firewood, agricultural residues, etc. The main process in a 3SF is the combustion of fuel, which can simplistically be considered a complete oxidation of biomass (Joos, 2006; Kaltschmitt, 2009). Thus, the fuel (containing C as energy carrier) and ambient air (providing the stoichiometric amount of oxygen) are required as $\dot{m}_{input}$. The $\dot{m}_{output}$ includes ash as residues and exhaust gases as emissions (Fig. A.1). Oxidation of fuel is an exothermic reaction so that heat (and light) is released to the direct surrounding of the fireplace.

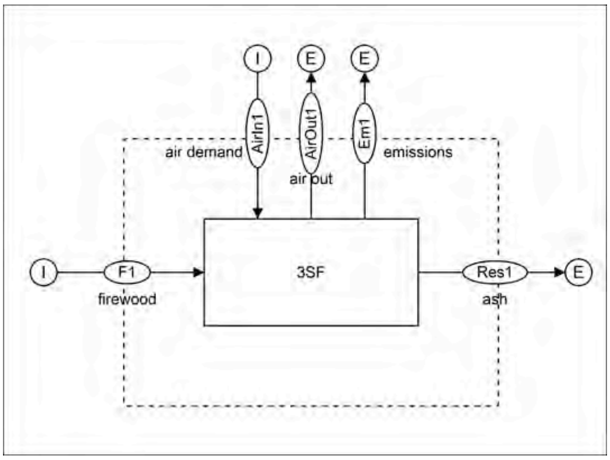


Figure A.1: STAN-model of the alternative E1, the three-stone-fire (3SF).

Alternative E2: A charcoal burner is used when cooking with charcoal. The main process is the complete combustion/oxidation of biomass, which takes place in an insulated combustion chamber (Fig. A.2). Beforehand, the charcoal is produced via the process of pyrolysis whereby wood is used as fuel. In addition to the emissions from cooking on the charcoal burner, further gaseous, liquid, and solid (i.e. ash and brands) emissions arise from the charcoal production. Ash is the main residue from burning charcoal.

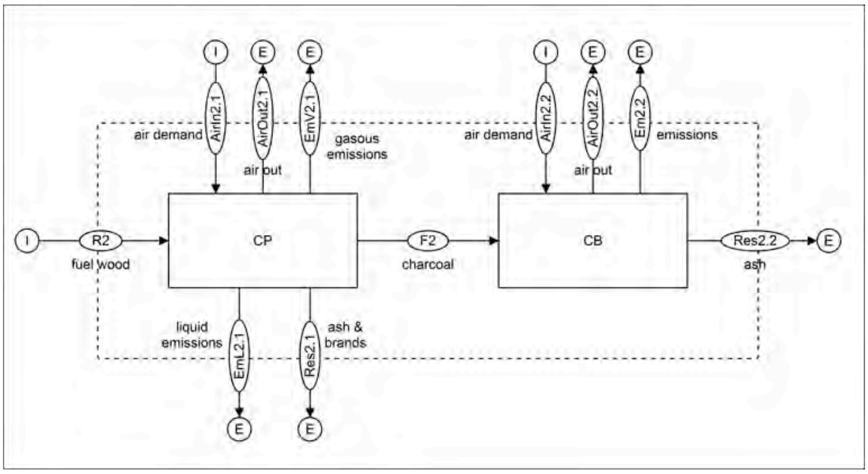


Figure A.2: STAN-model of the alternative E2, including charcoal production (CP) and charcoal burner (CB).

Alternative E3: A rocket stove is in principle comparable to a three-stone-fire. The main process is also the complete combustion/oxidation of biomass (Fig. A.3), which takes place in an insulated combustion chamber. Ash is the main residue after burning the firewood.

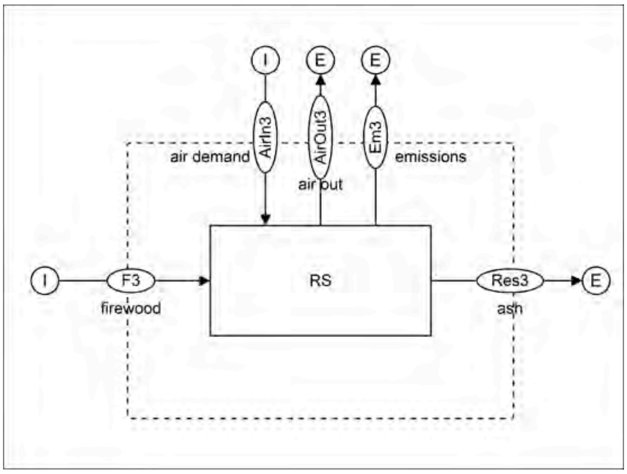


Figure A.3: STAN-model of the alternative E3, the rocket stove (RS).

Alternatives E4 and **E5**: The specific design of the microgasifier facilitates the existence of a so-called "primary" and a "secondary" air flow, which spatially separates (i) the transformation of biomass into combustible wood-gas from (ii) the subsequent oxidation of the gas (Anderson et al., 2007; Mukunda et al., 2010; Roth, 2011). The first process takes place in the bottom and centre of the stove, whilst the latter is realized in the top of the stove, which is called the "combustor". Apart from heat, powdery charcoal is produced as a by-product (McLaughlin et al., 2009). Thus, the residue after cooking with a microgasifier stove rather consists of ash and char instead of ash only. In alternative E4 (Fig. A.4), we analysed a microgasifier using a powdery fuel (i.e. sawdust) whilst the stove analysed in alternative E5 (Fig. A.5) uses firewood as fuel. The process of gasification of fuel with the subsequent oxidation of gas is similar in both designs of microgasifier stoves, only the used fuel causes slight differences in the design.

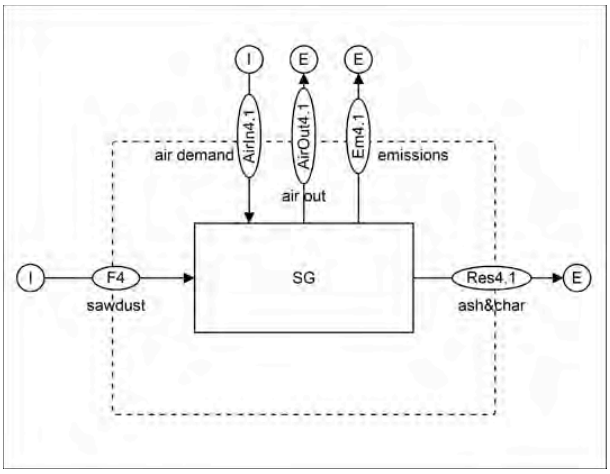


Figure A.4: STAN-model of the alternative E4, the sawdust gasifier (SG).

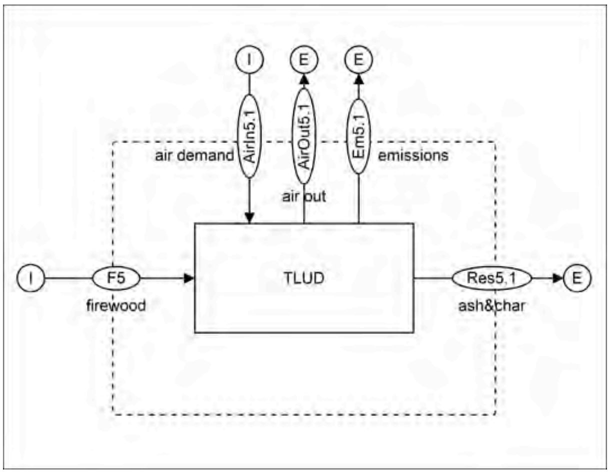


Figure A.5: STAN-model of the alternative E5, the TLUD-gasifier stove.

Alternative E6: The biogas system (Fig. A.6) consists of a biogas digester (Fig. A.7) and the biogas burner, where the biogas is oxidized for cooking. When producing biogas, organic wastes are anaerobically digested via microbiological activity in a closed fermenter (Vögeli et al., 2014). This results in a methane-rich combustible gas as the main product and biogas slurry as a liquid residue. The produced biogas is usually collected inside the digester or in a separate storage tank. The technology of the case study follows the design of a plug flow reactor and uses mainly cut pieces of banana tree stem mixed with cow dung as the organic wastes. A certain share of the liquid biogas slurry is usually recycled to the digester together with the anaerobic microorganisms.

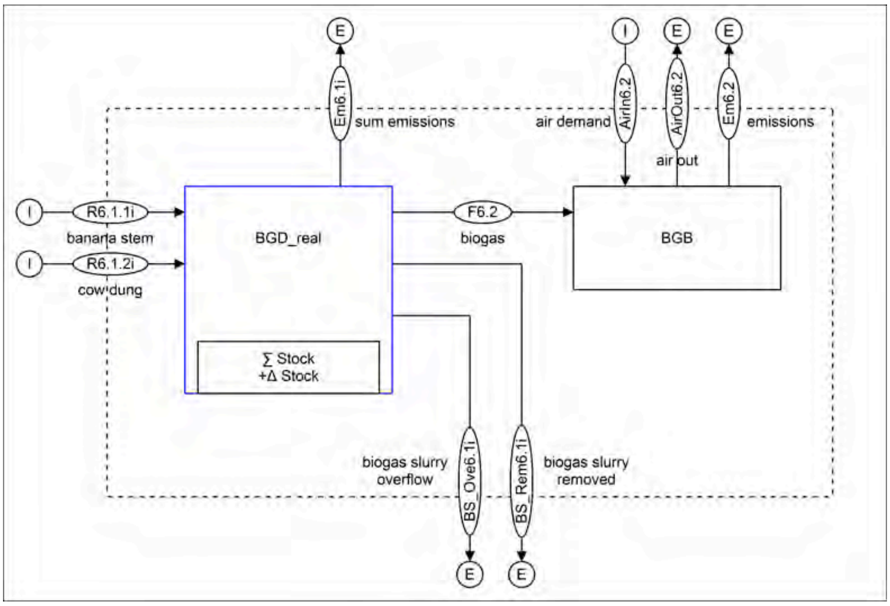


Figure A.6: STAN-model of the alternative E6, the biogas system including biogas digester (BGD) and biogas burner (BGB).

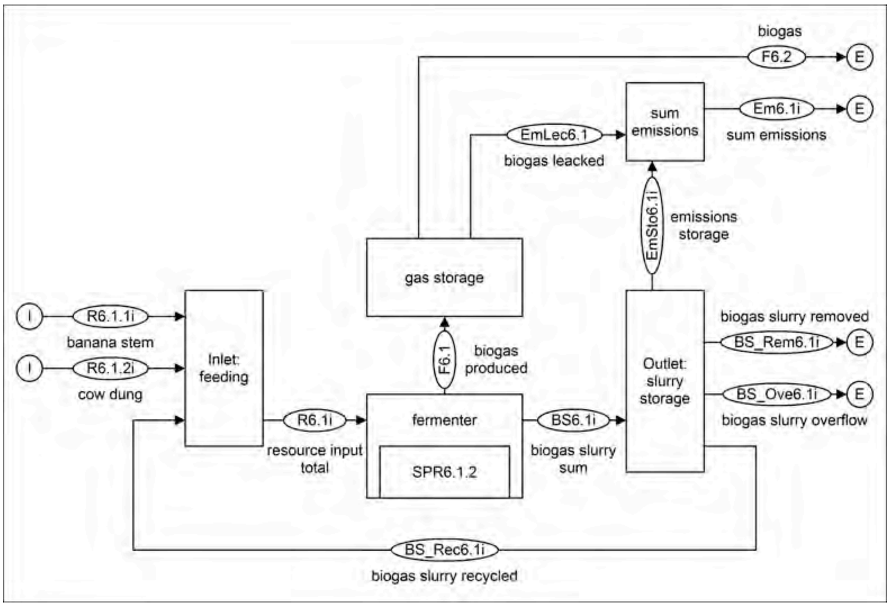


Figure A.7: STAN-model of the sub-process “BGD” of the alternative E6.

A.2. SPECIFIC SET OF EQUATIONS

When applying the main equation representing the "principle of mass conservation" (Eq. 1 of the main text), we first carried out the mathematical operations with the arithmetic mean value ($\bar{x}$). Then, we calculated the standard error (Δx), which derives from the standard deviation (σ) of the test series or collected data set as well as the relative uncertainty (RU), which is defined as Δx in % of $\bar{x}$ (Brunner and Rechberger, 2004). This corresponds to *Gauss's law of error propagation* (Brunner and Rechberger, 2004; FAU physics, n.d.), which differs for addition or subtraction (Eq. A.1 and A.2) and multiplication or division (Eq. A.3 and A.4).

If $y = c_1\bar{x}_1 + c_2\bar{x}_2 + \ldots + c_k\bar{x}_k$ with $c > 0$ (addition) and $c < 0$(subtraction) then:

$$\Delta y = \sqrt{(c_1\Delta x_1)^2 + (c_2\Delta x_2)^2 + \ldots + (c_k\Delta x_k)^2} \quad \text{Eq. (A.1)}$$

and $RU_y = \Delta y/\bar{y}$ Eq. (A.2)

If $y = c\bar{x}_1^{m_1} \cdot \bar{x}_2^{m_2} \cdot \ldots \cdot \bar{x}_k^{m_k}$ with $m > 0$ (multiplication) and $m < 0$ (division) then:

$$RU_y = \sqrt{(m_1 RU_1)^2 + (m_2 RU_2)^2 + \ldots + (m_k RU_k)^2} \quad \text{Eq. (A.3)}$$

and $\Delta y = RU_y \cdot \bar{y}$ Eq. (A.4)

To describe the energy conversion processes, we used the "process values from WBT" and "material and process values".

A.2.1. Input flows: required resources

I. Fuel consumption deriving from WBT-data

We first calculated the total fuel demand (F) for performing the cooking task separately for each phase of the WBT (Eq. A.5). Then the F of the three phases were added up to the total quantity of F needed to satisfy the energy demand of the model household in one year (Eq. A.6).

$$F_{G,wet,HP_{cold}} = \frac{\mathrm{MF} \cdot SUM_{HP_{cold}} \cdot m_{dry,HP_{cold}}}{(1 - mc_F)} \quad \text{Eq. (A.5)}$$

Exemplary for HP_cold where $F_{G,wet,HP_{cold}}$ is the total fuel in FM consumed as G in phase HP_cold; fac_{CO} is the net dry fuel consumed in HP_cold; for SUM and MF see Table A.1; mc_F is the moisture content of the fuel.

$$F_{G,wet} = F_{wet,HP_{cold}} + F_{wet,HP_{hot}} + F_{wet,LP} \quad \text{Eq. (A.6)}$$

Pre-heating does not affect the efficiency of certain stoves (e.g. microgasifiers and the biogas burner), whereas cooking with either three-stone-fire, charcoal burner, or rocket stove requires additional energy during HP_cold to heat the stones/insulation bricks. Hence, in testing these stoves we did not perform HP_hot and defined HP_hot to be equal to HP_cold in the alternatives E4 to E6 of our model.

We first calculated the fuel requirements on the layer of G ($F_{G,wet}$) and then split them further into C-, N- and P-flows, using elemental compositions (Eq. A.7, exemplary for the C-flow of F):

$$\mathrm{F_C} = \mathrm{F_{G,wet}} * \mathrm{c_{C,F,wet}} \quad \text{Eq. (A.7)}$$

According to the WBT-protocol (2014), data on fuel consumption must be collected as FM during the WBT ($F_{G,wet}$). Subsequently, the measured fuel consumption converts into the equivalent fuel consumed ($m_{eq,dry,consumed}$) in dry matter (DM). Thus, data from different WBTs conducted under varying circumstances are comparable. The mass of fuel needed merely for the evaporation of the fuel moisture is thereby excluded from $m_{eq,dry,consumed}$.

However, in our model, we used $m_{eq,dry,consumed,HP_{cold}}$ for $m_{dry,HP_{cold}}$ (Eq. A.5). Hence, our calculated fuel requirements slightly underrate the real fuel demand.

II. Resource consumption for the production of charcoal

Alternative E2 in our model consists of two elements, i.e. charcoal production and charcoal burner (Fig. A.2). The WBT-data determined the daily and annual charcoal consumption in a household, as explained above. But, first, one needs to produce charcoal, which in TZ is usually done via pyrolysis in earth kilns (Ellegård et al., 2003; Msuya et al., 2009; Nahayo et al., 2013). The underlying process can be considered a slow pyrolysis consuming wood, with a minimum residence time of one hour and a heating rate of < 100° K min^{-1} (*ibid.*). Additionally, we collected data on the conversion of input materials (usually wood) into gaseous, liquid (i.e. water and non-water liquids) and solid (i.e. charcoal, brands and ash) products (Adam, 2009; Kammen and Lew, 2005; Malimbwi and Zahabu, 2009; Msuya, 2011; Pennise, 2001). From this, we calculated average values for the mass fraction (frac) of the different pyrolysis products (Table A.3).

Table A.3: Mass fractions of pyrolysis products.

frac	% (wood in DM)
Ash/brands	0.05 ± 0.02
Charcoal	0.21 ± 0.03
Gases	0.49 ± 0.04
Water	0.14 ± 0.01
Non-water liquids	0.11 ± 0.01

The amount of firewood required as a resource (R) for producing charcoal was calculated as follows:

$$R_{G,dry} = F_{G,dry}/frac_{charcoal} \quad \text{Eq. (A.8)}$$

$$R_{G,wet} = R_{G,dry}/\ (1 - mc_R) \quad \text{Eq. (A.9)}$$

III. Resource consumption for the provision of biogas, considering biogas leakages

The elements for modelling alternative E6 are the biogas digester and the biogas burner (Figs. A.6 and A.7). Here, estimating the daily or annual biogas consumption was challenging since the available data of the WBT on biogas stoves varied in terms of the water amount used for testing (2, 4 and 5 dm^3). Hence, the "total energy consumed" and "cooking energy delivered to pot" varied for all WBT-phases. Therefore, we could not directly compare the collected data on fuel consumption. Nevertheless, we derived the average "efficiency" of biogas stoves. Furthermore, we found that, using 5 dm^3 of water, the "time-to-boil" in the WBT for biogas stoves was similar to that for wood-gasifier stoves (≈ 20 min.). Hence, we used WBT-data sets collected for microgasifier stoves (alternatives E4 and E5) and calculated the mean value of "cooking energy delivered to pot", which we then defined as the required energy input for the HP-phase. We calculated the required energy input for simmering by using the mean value for "cooking energy delivered to pot" during LP-phase from all other alternatives (E1 to E5). Then, we estimated "total energy consumed" (Eq. A.10), volume of biogas (Eq. A.11), and mass of biogas (Eq. A.12) required in E6.2 (exemplary for HP_cold):

$$total\ energy\ consumed_{HP_{cold}} = required\ energy\ input_{HP_{cold}}/efficiency_{HP_{cold}} \quad \text{Eq. (A.10)}$$

$$volume\ gas\ consumed_{HP_{cold}} = total\ energy\ consumed_{HP_{cold}}/LHV \quad \text{Eq. (A.11)}$$

$$m_{HP_{cold}} = mass\ gas\ consumed_{HP_{cold}} = volume\ gas\ consumed_{HP_{cold}} \cdot \rho_{biogas} \quad \text{Eq. (A.12)}$$

where efficiency is the mean efficiency of biogas stoves, LHV is the lower heating value [kJ m^{-3}], and ρ the density [kg m^{-3}] of biogas.

Since it is not relevant for biogas to distinguish between DM and FM, Eq. A.5 was adopted accordingly to determine F of biogas for each phase (Eq. A.13). Then, the annual biogas consumption in the household was estimated as explained above (Eq. A.6).

$$F_{G,HP_{cold}} = \text{MF} \cdot SUM_{HP_{cold}} \cdot m_{HP_{cold}} \quad \text{Eq. (A.13)}$$

Then, we calculated the required input of resources, i.e. **feeding substrates**. For this, we used data from the evaluation of the specific performance of the pilot BiogaST-digester. Initially, a so-called “first filling” is required to fill the reactor volume with substrates (i.e. ≈ 12 m^3), which amounted to 2,140 ± 215 kg cow dung and 9,700 ± 970 kg water. During the pilot operation in the case study, the daily feeding was mixed from banana stem (banana) and cow dung (Eq. A.14). Input material and output material were balanced according to the “principle of mass conservation” (Eq. 1; main text), so that the fermenter volume remained equally filled (Eq. A.15).

$$R_{tot,G,wet} = R_{banana,G} + R_{cow\ dung,G} \qquad \text{Eq. (A.14)}$$

$$m_{input} = m_{output} \qquad \text{Eq. (A.15)}$$

$$\Rightarrow m_{input,banane} + m_{input,cow\ dung} + m_{input,recycled\ slurry} = m_{output,removed\ slurry} + m_{output,biogas}$$

The material inputs of R were provided in a ratio of 1:2, i.e. one bucket of cow dung and two buckets of banana stem (1 bucket ≈ 20 dm^3). Given the recorded weight per bucket, we calculated the fraction of FM of banana stem ($frac_{banana}$) and cow dung ($frac_{cowdung}$) in kg kg^{-1} of $R_{tot,G,wet}$. Then, we determined the required daily amount of each of the two feeding substrates (Eq. A.16, exemplary for cow dung).

$$R_{cow\ dung,G} = R_{tot,G,wet} \cdot frac_{cow\ dung,G} \qquad \text{Eq. (A.16)}$$

According to literature (e.g. Gyalpo, 2010; Vögeli et al., 2014), some of the total biogas produced gets commonly lost because of **leakages** (e.g. in the cover of the gas storage or in the piping system), which on average amounts to ≈ 18.5 ± 1 m^3 m^{-3} ($frac_{leakage}$, Eq. A.17). This biogas loss was factored in to determine the total amount of biogas that the biogas digester needs to produce to meet the biogas need of the household (F_G) (Eq. A.18).

$$biogas_{produced} = F_G/(1 - frac_{leakage}) \qquad \text{Eq. (A.17)}$$

$$biogas_{produced} = biogas_{lost} + biogas_{used} = biogas_{leaked} + F_G \qquad \text{Eq. (A.18)}$$

On this basis, we determined the total amount of resources required for fermentation ($R_{G,wet}$):

$$R_{tot,G,wet} = \frac{biogas_{produced}}{\rho_{biogas} \cdot SGP \cdot c_{VS,tot,dry} \cdot (1 - mc_{tot,wet})} \qquad \text{Eq. (A.19)}$$

where SGP is the Specific Gas Production of the digester [m^3 kg VS]; $c_{VS,tot,dry}$(Eq. A.24) is the concentration of Volatile Substances (VS) in $R_{tot,G,wet}$; and $mc_{tot,wet}$ (Eq. A.23) is the content of moisture in $R_{tot,G,wet}$.

We considered and integrated the **level of technological maturity** in our model. In reality, the digester of the BiogaST-project remains under development and we expect further improvements in the performance, especially through the initiated cooperation with the Tanzania Domestic Biogas Programme (TDBP)[2]. Hence, in E6, we distinguished between (i) an “ideal” scenario (E6.1.i) and (ii) the “real” scenario (E6.2.r). Differences in the two sub-scenarios are based on varying reactor performance, which are expressed with the specific gas production (SGP) of the digester. In E6.1.i, we used the potential SGP of cow dung and banana stem, as derived from laboratory testing by Knaebel (2006) (see Table A.6) (Eq. A.20). And in E6.1.r, we derived the SGP from data evaluation of the BiogaST pilot digester at MAVUNO (Eq. A.21 and 22).

$$\text{SGP}_{ideal} = \frac{SGP_{pot,banane} \cdot m_{banane,VS} + SGP_{pot,cow\ dung} \cdot m_{cow\ dung,VS}}{m_{tot,VS}} \qquad \text{Eq. (A.20)}$$

where $SGP_{pot,banane}$ and $SGP_{pot,cowdung}$ are the potential SGP of the two feeding substrates [m^3 kg^{-1} of VS] and $m_{banane,VS}$ is the matter of VS in banana material fed to the digester [kg day^{-1}] ($m_{cowdung,VS}$ and $m_{tot,VS}$ were defined for the input of cow dung and total matter respectively). According to the above-mentioned assumption, $m_{banane,VS}$ is the VS contained in two buckets of banana material and $m_{cowdung,VS}$ is the VS contained in one bucket of cow dung.

[2] Implemented by the CAMARTEC, based in Arusha, Tanzania.

$\text{SGP}_{real} = biogas_{produced}/m_{tot,VS}$ Eq. (A.21)

$m_{tot,VS} = m_{tot,G,wet} \cdot (1 - mc_{m_{tot},wet}) \cdot c_{VS,m_{tot},dry}$ Eq. (A.22)

where SGP_{real} is the average SGP [m^3 kg VS] observed in the pilot study when feeding $m_{tot,G,wet}$ [kg day^{-1}].

The moisture content of the mixed feeding substrates ($mc_{tot,wet}$; Eq. A.23) and the concentration of VS in the mixture ($c_{VS,m_{tot},dry}$; Eq. A.24) were determined from specific parameters of the two input substrates.

$$mc_{tot,wet} = \frac{m_{banana,G,wet} \cdot mc_{banana,wet} + m_{cowdung,G,wet} \cdot mc_{cow\ dung\ ,wet}}{m_{tot,G,wet}} \quad \text{Eq. (A.23)}$$

$$c_{VS,tot,dry} = \frac{m_{banana,G,wet} \cdot (1-mc_{banana,wet}) \cdot c_{VS,R_{banana},dry} + m_{cow\ dung,G,wet} \cdot (1-mc_{cow\ dung,wet}) \cdot c_{VS,cow\ dung,dry}}{m_{tot,G,wet} \cdot (1 - mc_{tot,wet})} \quad \text{Eq. (A.24)}$$

In accordance with this approach, we estimated R_{tot} for both sub-scenarios E6.1.i and E6.1.r by applying Eq. A.22 with SPG_{ideal} and SPG_{real}, respectively, and derived R_{banana} and $R_{cow\ dung}$ using Eq. A.16. Then, we calculated the means of all relevant values from E6.1.r and E6.1.i to present average results for E6.

A.2.2. Output flows: residues from the energy conversion process

For our model, we deemed the energy conversion process an ideal and perfect combustion (Joos, 2006; Kaltschmitt, 2009). This means, the elements C, N, H, S, and O contained in biomass are completely oxidised and subsequently found in the exhaust gases (*ibid.*). Solid residues (Res) also remain after the energy conversion process.

I. Ashes as residues from alternatives E1 to E3

Ashes of mineral content remain after the combustion of firewood (E1, E3) or charcoal (E2) and are quantitatively estimated with:

$Res_{G,wet} = F_{G,wet} * c_{F,ash,wet}$ Eq. (A.25)

where $c_{ash,wet}$ is the concentration of ash in FM of F.

Based on these assumptions, there was no N left in the ashes and $Res_N \stackrel{\text{def}}{=} 0$. According to Lehmann and Joseph (2009), the volatilisation temperature of P is above 700-800° C. So, we assumed all P is transferred from fuel to ash and $Res_P \stackrel{\text{def}}{=} F_P$.

In E2, ash and brands ($Res_{pyr,ash/brand}$) remained as additional solid products from charcoal production and were calculated according to Table A.3. However, charcoal is usually not produced at the consumers' homes, therefore, this flow was not considered as a recycling flow but treated as an output flow. We assumed that $Res_{pyr,ash/brnads}$ consists of 50 % ash and 50 % brands (i.e. partly charred particles or "not fully converted wood"; Pennise et al., 2001). We estimated the concentrations of C and N in brands, assuming an average composition of 50 % wood and 50 % char particles and using elemental concentrations of wood and charcoal. Subsequently, we calculated C- and N-layers of $Res_{pyr,ash/brands}$. For the P-layer, we simplistically assumed that P is distributed to solid products only. Thus, we first calculated how much P was transformed from wood to charcoal products (Eq. A.26) and, then, how much remained in ash and brands (Eq. A.27).

$F_P = R_P \cdot frac_{charcoal}$ Eq. (A.26)

$Res_{pyr,P,ash/brand} = R_P - F_P$ Eq. (A.27)

II. Ash and char as residues from alternatives E4 and E5

In the two alternatives using gasifier stoves for cooking, the total thermal energy conversion process comprises (i) gasification of fuel (e.g. firewood, sawdust, etc.) in an oxygen-limited environment inside the stove, and (ii) oxidation of the arising wood gas. Char forms as a by-product in addition to ash ("ash & char", $Res_{gasi,ash\&char}$). In compliance with the principles of Terra Preta (Glaser et al., 2002; Sombroek, 1966), we considered $Res_{gasi,ash\&char}$ to be a potential recycling flow that could be utilized as a compost additive termed biochar (Lehmann and Joseph, 2009; Kammann et al., 2015).

We collected data on the amount of $Res_{gasi,ash\&char}$ that remains after cooking with various gasifier stoves ($frac_{ash\&char}$ given in mass percentage of the fuel; Eq. A.28) for both analysed technologies.

$$Res_{gasi,ash\&char,G,wet} = F_{G,wet} * frac_{ash\&char} \quad \text{Eq. (A.28)}$$

However, if the matter of $Res_{gasi,ash\&char}$ remains inside the stove after cooking whilst heat and oxygen are present, the remaining char particles might be further oxidised. This reduces the amount of residues available from cooking. To avoid these thermo-chemical processes, the stove needs to be either completely closed after cooking (e.g. with a flap or door covering the air inlets) or emptied to extinguish $Res_{gasi,ash\&char}$ separately (e.g. putting it in an air-tight container or covering the matter with water, sand, or soil).

Consequently, we investigated changes in the quantitative recovery of $Res_{gasi,ash\&char}$ for both options: (i) emptying the stove or extinguishing the char material directly after cooking, and (ii) leaving $Res_{gasi,ash\&char}$ inside the open stove until the next morning, when it would have become $Res^{*}_{gasi,ash\&char}$. To represent this **"next morning" scenario**, we added the scenarios E4* and E5* to E4 and E5 (Figs. A.8 and A.9).

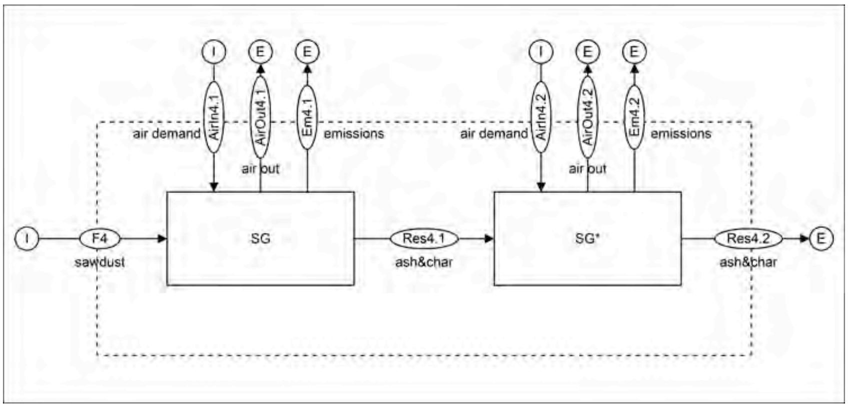


Figure A.8: STAN-model of the alternative E4*, the sawdust gasifier (SG) in the scenario "next morning".

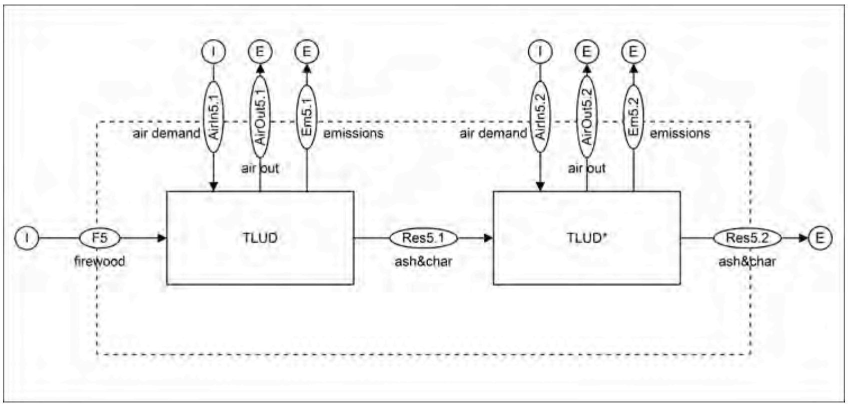


Figure A.9: STAN-model of the alternative E5*, the TLUD gasifier in the scenario "next morning".

We empirically determined the quantitative difference in residues available "after cooking" or "next morning" to estimate the mass percentages of $Res_{gasi,ash\&char}$ and $Res^{*}_{gasi,ash\&char}$. For this, we conducted an on-site experiment with both gasifier stoves at CHEMA's workshop. We measured F before cooking, $Res_{gasi,ash\&char}$ directly after the open fire extinguished, and $Res^{*}_{gasi,ash\&char}$ available the next morning. Replications were n = 2 for the sawdust gasifier and n = 3 for the TLUD-stove. Then, we approximated the conversion factors $frac_{ash\&char}$ (Eq. A.29) and $frac^{*}_{ash\&char}$ (Eq. A.30) in mass percentage of the fuel in FM.

$$frac_{ash\&char} = Res_{gasifier,ash\&char}/F_{G,wet} \qquad \text{Eq. (A.29)}$$

$$frac^{*}_{ash\&char} = Res^{*}_{gasifier,ash\&char}/F_{G,wet} \qquad \text{Eq. (A.30)}$$

Data on the elemental composition of $Res_{gasi,ash\&char}$ was collected through literature review. In addition, we sampled $Res^{*}_{gasi,ash\&char}$ from the experiment above. Using a thermal conductivity detector (CNS-Analyser, Vario ELIII, Elementar, Hanau, Germany) and the method according to ISO DIN 10694 (1995), we analysed the content of total C after dry combustion of oven-dry material. Furthermore, we assumed that the remaining N contained in $Res_{gasi,ash\&char}$ would be oxidised over night ($\Rightarrow Res^{*}_{gasi,ash\&char,N} \stackrel{\text{def}}{=} 0$) and set $F_P \stackrel{\text{def}}{=} Res_{gasi,ash\&char,P} \stackrel{\text{def}}{=} Res^{*}_{gasi,ash\&char,P}$.

III. Biogas slurry as residue from alternative E6

The residue from anaerobic fermentation is called biogas slurry (also called bio-slurry, or digestate). Part of the daily proceedings of operating the BiogaST pilot digester was to remove some biogas slurry and **use it as fertilizer** ($Res_{biogasslurry,removed,daily,G}$). Other matter was removed from the outlet and refilled into the inlet of the digester ($Res_{biogasslurry,recycled,daily,G}$). This **recycling of biogas slurry** was practiced (i) to substitute water, which is required to make sure that the input feeding material is liquid enough to enter the biogas digester, and (ii) to recycle microbes contained in the slurry that are crucial for the fermentation process. The ratio of these material flows in terms of volume was 1:5, i.e. every day one bucket of biogas slurry was removed and five buckets were recycled.

In addition, the BiogaST-digester is designed and constructed with a so-called "**overflow**", which is an opening in the digester outlet. Here, biogas slurry can automatically stream out of the fermenter by gravity. This happens for example if in- and output flows are not balanced according to Eq. A.15 and the sludge volume therefore exceeds the reactor volume. In the pilot project, an open compost heap was placed underneath the overflow so that the biogas slurry remained there and could be used as fertilizer later, during the planting period. But, unfortunately, neither the quantities that were used in agriculture nor the period of time for which the matter remained at the compost were specifiable, because there was no data collection on overflowing material during the pilot phase of the case study.

Nevertheless, we deduced **transfer coefficients** (TC) from the project data to estimate the material flows of biogas slurry that is removed (Eq. A.31) or recycled (Eq. A.32) in mass percentage of the total feeding substrates.

$$TC_{biogas\ slurry,removed} = Res_{biogas\ slurry,removed,daily,G}/R_{daily,G,wet} \qquad \text{Eq. (A.31)}$$

$$TC_{biogas\ slurry,removed} = Res_{biogas\ slurry,recycled,daily,G}/R_{daily,G,wet} \qquad \text{Eq. (A.32)}$$

where $R_{daily,G,wet}$ is the weight of planned input of total biomass resources in FM per day, with the ratio of 1:2 buckets for cow dung : banana stem; $R_{biogasslurry,removed,daily,G}$ is the weight of one bucket of biogas slurry removed; and $R_{biogasslurry,recycled,daily,G}$ is the weight of five buckets of biogas slurry recycled.

Given the annual R input $R_{tot,G}$ (Eq. A.19), we derived the total amount of biogas slurry to be removed (Eq. A.33) or recycled (Eq. A.34).

$$Res_{biogas\ slurry,removed,tot,G} = TC_{biogas\ slurry,removed} \cdot R_{tot,G} \qquad \text{Eq. (A.33)}$$

$$Res_{biogas\ slurry,recycled,tot,G} = TC_{biogas\ slurry,removed} \cdot R_{tot,G} \qquad \text{Eq. (A.34)}$$

Moreover, we estimated the amount of biogas slurry leaving the digester via the overflow to close the mass balance of the biogas digester (Eq. A.35).

$$Res_{biogas\ slurry,overflow,tot,G} = R_{tot,G} - Res_{biogas\ slurry,removed,tot,G} - biogas_{produced} - EM_{tot} \quad \text{Eq. (A.35)}$$

Note: $Res_{biogasslurry,recycled,tot,G}$ was not included in the equation because the amount removed through the outlet and the amount filled into the inlet are equal, hence, they offset each other in mass balancing.

A.2.3. Output flows: emissions from energy conversion process and oxygen/air demand

The WBT-protocol (2014) discusses the physical principles of quantifying pollutants and provides an overview of technical options for conducting **measurements**. The Regional cookstoves Testing and Knowledge Centre (RTKC)[3] uses a portable emissions monitoring system (PEMS)[4]. Here, samples are continuously captured from the exhaust gas stream and subsequently analysed for the content of CO, CO_2, and PM with a size of 2.5 µm ($PM_{2.5}$). The total emissions are measured and then correlated to the dry fuel mass. Oxygen or air demand is usually not documented. During evaluation of the WBT-data, we faced difficulties in assessing the quality and accuracy of the emission data, especially those on $PM_{2.5}$ and CH_4, but concluded they are not sufficient (e.g. negative values for $PM_{2.5}$ in the data set). Dialogue with the cooperating partners revealed problems with the equipment for measuring PM. Moreover, we found a high variation in the data on emissions in WBT from different sources. Also, the equipment used for the measurements varied from study to study. Ultimately, we did not use these data.

In turn, **assuming a complete oxidation process** gave us the opportunity to estimate combustion emissions (EM_{comb}) and the amount of oxygen required (AirIn) to convert a given fuel flow into thermal energy to enable the cooking task. The exhaust flow, as export flow from MES to the atmosphere, comprised all EM_{comb} and the amount of air that left the MES again (AirOut).

I. Applied stoichiometry for modelling the energy conversion process

According to Joos (2006) and Kaltschmitt (2009), we defined the following **reaction equilibriums** for the oxidation of C, H and S:

$$C + O_2 \rightarrow CO_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$S + O_2 \rightarrow SO_2$$

The content of C, H, N, S and O in biomass is calculated by using the respective element concentrations derived from literature (see Table A.12). If we assume ideal combustion, all C contained in the biomass is converted to CO_2. However, in practice, not only CO_2 emerges (m_{CO_2}) but also CO (m_{CO}). Based on emission data from experimental measurements, we defined the "CO-factor" (fac_{CO}) to further quantify the percentage of C converted to CO instead of CO_2 (Eq. A.36). Thus, fac_{CO} to a certain degree indicates the efficiency of carbon oxidation for the various stoves.

$$fac_{CO} = \frac{m_{CO}}{m_{CO} + m_{CO_2}} \quad \text{Eq. (A.36)}$$

The respective reaction equilibrium is:

$$2C + O_2 \rightarrow CO$$

According to Joos (2006), the conversion of N into various possible products strongly depends on the stoichiometry and on the temperature. In the assumed stoichiometric conditions in the stoves and with reaction temperatures below

[3] The RTKC is located at the CREEC at Makere University in Kampala, Uganda.

[4] From Aprovecho Research Center, Cottage Grove, USA; see: http://www.aprovecho.org/lab/emissionsequip/pems.

1000° C, the formation of thermal and prompt NO_x is neglectable and was not considered in our model. Nevertheless, in the prevailing conditions, it is most likely that one third of N contained in $F_{G,wet}$ converts into NO and two thirds into N_2 (Joos, 2006). The reaction equilibrium for forming NO is:

$$N_2 + O_2 \rightarrow 2NO$$

II. Determining emissions and oxygen demand

In compliance with the above-mentioned reaction equilibriums, the oxygen (O_2) demand and the resulting EM_{comb} are determined for each reaction specifically. For this, we calculated O_2- and EM-factors, which are based on the content of reacting elements in the fuel (Table A.4). For example, 2.7 kg O_2 are required to convert 1 kg C (contained in fuel) into 3.7 kg CO_2.

Table A.4. Summary of reaction equilibriums assumed for complete oxidation of biomass and O_2- and EM-factors.

Reaction equilibrium	O_2-factor [1]	EM-factor [1]
$C + O_2 \rightarrow CO_2$	2.7	3.7
$2C + O_2 \rightarrow CO$	1.3	2.3
$2H_2 + O_2 \rightarrow 2H_2O$	7.9	8.9
$S + O_2 \rightarrow SO_2$	1.0	2.0
$N_2 + O_2 \rightarrow 2NO$	1.1	2.1

The unit of both factors is mol mol^{-1} or kg kg^{-1} or 1.

Then, we calculated the specific and **stoichiometric oxygen demand** (OD) per kg DM of fuel (e.g. OD_{stoich,CO_2}; Eq. A.37) and the model values of OD, i.e. the annual OD in kg O_2 required to perform the cooking task (OD_{model,CO_2}; Eq. A.38).

$OD_{stoich,CO_2} = 2.7 \cdot c_{F,C,dry}$ Eq. (A.37)

$OD_{model,CO_2} = F_{G,wet} \cdot (1 - mc_F) \cdot OD_{stoich,CO_2} \cdot (1 - fac_{CO})$ Eq. (A.38)

Equations are exemplary for the reaction $C + O_2 \rightarrow CO_2$ where the O_2-factor is 2.7 and $c_{F,C,dry}$ is the total concentration of C in DM of fuel.

The total amount of O_2 to be imported to the household from the atmosphere, i.e. AirIn, is the sum of OD_{model} in all emissions reduced by the O_2 contained in the fuel (Eq. A.39).

$OD_{tot} = OD_{modell,CO_2} + OD_{modell,CO} + OD_{modell,N} + OD_{modell,S} + OD_{modell,H} - (F_{G,wet} \cdot (1 - mc) \cdot c_{F,O,dry})$ Eq. (A.39)

Given OD_{tot}, we calculated the total demand of air (AirIn; Eq. A.40).

$AirIn = OD_{tot}/0.231$ Eq. (A.40)

Here, we assumed a mean mass concentration of 23.1 % atmospheric O_2 in air.

For calculating AirOut, we assumed that O_2 in the air would be fully required for biomass conversion (Eq. A.41) and, thus, be transformed to EM. We further assumed that the main content in AirOut is N_2 from AirIn, which leaves the system again, so we set $AirOut \stackrel{\text{def}}{=} AirIn_N$.

$AirOut = AirIn - OD_{tot}$ Eq. (A.41)

The **emissions** were estimated stepwise, too. First, we calculated emissions from complete and stoichiometric combustion per kg DM of fuel ($EM_{comb,stoich}$; Eq. A.42), followed by total emissions of the annual model in kg of the respective emission ($EM_{comb,model}$; Eq. A.43).

$EM_{comb,stoich,CO_2} = 3.7 \cdot c_{F,C,dry}$ Eq. (A.42)

$$EM_{comb,model,CO_2} = F_{G,wet} \cdot (1 - mc_F) \cdot EM_{comb,stoich,CO_2} \cdot (1 - fac_{CO})$$ Eq. (A.43)

Equations are exemplary for the reaction $C + O_2 \rightarrow CO_2$.

Then, we derived the total emissions ($EM_{comb,tot}$) from the sum of $EM_{comb,model}$ for all components of the emissions plus the amount of water vapour from the moisture content in the fuel ($EM_{moisture}$; Eq. A.44).

$$EM_{comb,tot} = EM_{comb,CO_2} + EM_{comb,CO} + EM_{comb,N_2} + EM_{comb,NO} + EM_{comb,SO_2} + EM_{comb,H_2O} + EM_{moisture}$$ Eq. (A.44)

Note: for simplification, EM_{comb} represents $EM_{comb,model}$.

III. Modifications for determining emissions and oxygen demand in the gasifier alternatives

For the alternatives E4 and E5, we calculated the content of the elements H, C, N, S, O in wood gas by quantifying the **difference in the elemental composition** of F and $Res_{gasi,ash\&char}$, which we termed "decomposed components". Subsequently, we modelled the oxidation of wood gas using the factors provided in Table A.4. However, as there is no differentiation between DM and FM for gases, these factors were directly multiplied with the element content in wood gas to get the model values for OD (Eq. A.45) and EM (Eq. A.46). We did not model the transformation of sawdust or firewood into wood gas via gasification as a separate process (i.e. not implemented in STAN) but considered it as stove-internal and therefore calculated it in Excel.

$$OD_{comb,modell,CO_2} = 2.7 \cdot (F_C - Res_{gasi,ash\&char,C})$$ Eq. (A.45)

$$EM_{comb,modell,CO_2} = 3.7 \cdot (F_C - Res_{gasi,ash\&char,C})$$ Eq. (A.46)

Equations are exemplary for the reaction $C + O_2 \rightarrow CO_2$ with an O_2-factor of 2.7 and an EM-factor of 3.7 (Table A.4).

Then, we calculated EM and OD for E4* and E5* with the same equations. Here, the decomposed elements were determined through difference in the elemental composition of $Res_{gasi,ash\&char}$ and $Res^{*}_{gasi,ash\&char}$.

IV. Additional emissions from charcoal production

In addition to Table A.3, Lehmann and Joseph (2009) and Pennise et al. (2001) provided emission factors for various **components of the gaseous product** emitted during the pyrolysis process, in kg of emission per kg of charcoal produced. In our model, the gaseous emissions CO_2, CO, CH_4, total non-methane hydrocarbons (TNMHC), NO_x, and PM were taken into account. We simplified these calculations by assuming that TNMHC is only ethane (C_2H_6) and NO_x is only NO_2. Furthermore, we converted given emission factors into fractions of each gaseous component in mass-% of the total gaseous product (e.g. $frac_{gases,CO2}$; Table A.5).

Table A.5: Mass fractions of gaseous pyrolysis products.

$frac_{gases}$	% (gas product)
CO_2	0.79 ± 0.20
CO	0.09 ± 0.02
CH_4	0.02 ± 0.004
TNHMC	0.03 ± 0.01
NO_x	0.00003 ± 0.00001
PM	0.06 ± 0.04

Then, we determined the annual emissions from pyrolysis specifically for all compounds (Eq. A.47):

$$EM_{pyr,CO_2} = R_{G,dry} \cdot frac_{gases} \cdot frac_{gases,CO_2}$$ Eq. (A.47)

Exemplary for the reaction $C + O_2 \rightarrow CO_2$ with $frac_{gases}$ provided in Table A.2 and $frac_{gases,\,CO2}$ provided in Table A.4.

Further, we compared N and H contained in wood, charcoal and **solid residues** (ash & brands). We explained the quantitative difference with additional emissions of N_2 and H_2 during pyrolysis. Then, we calculated the total gaseous pyrolysis products ($EM_{pyr,gases,tot}$; Eq. A.48).

$$EM_{pyr,gases,tot} = \sum EM_{pyr,CO_2} + EM_{pyr,CO} + EM_{pyr,CH_4} + EM_{pyr,C_2H_6} + EM_{pyr,NO_2} + EM_{pyr,PM} + EM_{pyr,N_2} + EM_{pyr,H_2}$$

Eq. (A.48)

Liquid emissions from pyrolysis (EmL; Eq. A.49 and A.50), comprise (i) condensed water vapour, which accounts for the difference of moisture in wood and charcoal ($EM_{pyr,moisture}$), (ii) water as a product according to Table A.3 ($EM_{pyr,water}$), and (iii) non-water liquid products ($EM_{pyr,nonwaterliquids}$), which are mainly tars (Msuya et al., 2011; Lehmann and Joseph, 2009).

$$EmL_G = EM_{pyr,moisture} + EM_{pyr,water} + EM_{pyr,non\,water\,liquids}$$ Eq. (A.49)

$$EM_{pyr,water} + EM_{pyr,non\,water\,liquids} = R_{G,dry} \cdot (frac_{water} + frac_{non-water})$$ Eq. (A.50)

Equation A.50 is a combination of Eq. A.9 applied for both water and non-water products and frac-values from Table A.3.

Moreover, we assumed (i) the concentration of C in PM to be 100 % and (ii) an elemental composition $EM_{pyr,nonwaterliquids}$ of ≈ 28 % O, ≈ 60 % C, and ≈ 9 % H, as described by Williams (1996). On this basis combined with the elemental composition of other gaseous compounds, we calculated $EM_{pyr,tot}$ on the C- and N-layer.

In general, pyrolysis is a thermochemical conversion process that takes place without or with little oxygen (Kaltschmitt, 2009). In our model, we estimated $OD_{pyr,tot}$ from the O_2 contained in $EM_{pyr,tot}$ minus O_2 provided by the fuel (Eq. A.51). Calculations of AirIn and AirOut were performed according to Eq. A.40 and A.41.

$$\mathrm{OD_{pyr,tot}} = \mathrm{EM_{O,pyr,tot}} - \mathrm{R}_O$$ Eq. (A.51)

V. Additional emissions from biogas digester

In the alternative E6, we calculated EM and OD from oxidation of biogas in a biogas burner as stated above. In addition, **emissions from the biogas digester** (Eq. A.52) include (i) biogas leaching (Gyalpo, 2010; Vögeli et al., 2014; Eq. A.53) and (ii) emissions from stored biogas slurry (Amon, 2006; Wang, 2014; Eq. A.54). According to Clemens et al. (2006) emissions of N during fermentation are neglectable.

$$EM_{BGD,tot} = EM_{leakage} + EM_{storage}$$ Eq. (A.52)

$$EM_{leakage,G} = biogas_{leakage,G} = biogas_{produced} \cdot frac_{leckage}$$ Eq. (A.53)

$$EM_{storage,G} = \sum TC_{EM,storage,G} \cdot \left(Res_{biogas\,slurry,recyled,tot,G} + Res_{biogas\,slurry,removed,tot,G} + Res_{biogas\,slurry,overflow,tot,G}\right)$$

Eq. (A.54)

where $\sum TC_{EM,storage}$ is the sum of emissions (CH_4, CO_2,N_2O, NH_3) from storage of slurry in g m^{-3} (see Table A.12).

We calculated the emissions from leaching on C- and N-layer with the average elemental composition of biogas (Table A.12). Emissions from storing biogas slurry on C- and N-layer were estimated by calculating $\sum tc_{EM,storage,C}$ and $\sum tc_{EM,storage,N}$, respectively.

A.3. Assessment of emissions to the environment

A.3.1. Assessment of greenhouse gas emissions to the atmosphere

We estimated the global warming potential (GWP) for the calculated gaseous emissions in compliance with the procedure of the Intergovernmental Panel on Climate Change (IPCC) published by Myhre (2013). For this, we used GWP_{100}-factors[5] (Table A.6) and multiplied these with the quantified material flows of emission components, which are specifically relevant in terms of climate change.

Table A.6: The GWP-factors used in this analysis; according to Myhre (2013).

Emission component	GWP_{100}-factor
CO_2	1
CO	2
CH_4	28
N_2O	265
TNMHC	4.5
NO	-11

The unit of the factor is kg CO_2e kg^{-1}.

We determined the total greenhouse gas (GHG) emissions of a single MES-alternative by summing up all emissions evaluated by their GWP_{100}-factors and expressed in CO_2-equivalents per household and year [kg CO_2e hh^{-1} yr^{-1}]. Pursuant to Gómez et al. (2006), we considered CO_2 emissions from bioenergy merely as information to compare a possible decrease or increase in GHG emissions between the various technologies. As mentioned above, we did not consider PM emissions in our system analysis due to lack of appropriate and reliable data from either the case studies or literature. However, PM can be assigned to "black carbon" which is assessed with a GWP of 100-1700 (Myhre et al., 2013).

A.3.1. Assessment of nutrient emissions to the hydrosphere

Gaseous emissions of NO and NH_3 to the atmosphere additionally contribute to nutrient transfers to the hydrosphere. Once in the air, the gases react with sulphuric acid and nitric acid and precipitate in the form of salt, which can easily be relocated to the pedosphere or hydrosphere. In addition, the salts dissolve easily in water, which can lead to an accumulation of nutrients in the water bodies and consequently to excessive growth of plants and algae (i.e. eutrophication).

We estimated the eutrophication potential (EP) in compliance with the procedure of the Institute of Environmental Science at the University of Leiden published by Heijungs et al. (1992) and Guinée (2002). For this, we used the EP-factors (Table A.7) and multiplied these with the quantified material flows of emission components, which are specifically relevant in terms of eutrophication.

Table A.7: The EP-factors used in this analysis; according to Heijungs et al. (1992) and Guinée (2002).

Emission component	EP-factor
NO	0.13
NH_3	0.35

The unit of the factor is kg PO_4e kg^{-1}.

We determined the total EP of a single alternative by summing up the NO and NH_3 emissions assessed with the respective EP-factors. The EP is expressed in PO_4-equivalents per household and year [kg PO_4e hh^{-1} yr^{-1}].

[5] GWP for a time horizon of 100 years (Myhre et al., 2013).

A.4. DATA EVALUATION

A.4.1. The WBT-data characterising the analysed stoves

In sum, we used **WBT-data from various sources** (Table A.8). The stoves developed in Karagwe were tested by the WBT at CHEMA's workshop (EfCoiTa, 2014). Furthermore, we worked with the RTKC in Kampala, Uganda. They conducted a WBT with the stoves from Karagwe and also measured emissions (CREEC, 2014). In addition, CREEC kindly provided WBT-data for 15 other stoves (including three-stone-fire, charcoal burner, and ICS), which they tested in the RTKC (CREEC, 2015). Awemu Biomass Ltd., a producer and distributor of TLUD-gasifier stoves from Kampala, also shared data on their stoves derived from WBT conducted at RTKC (Awemu, 2014). Moreover, we received WBT-data from the office of research and development of the United States Environmental Protection Agency, which tested and compared different ICS (Jetter and Kariher, 2009).

By evaluating the WBT-data, (i) we could characterise the analysed stoves and (ii) we derived data required for the MFA (Section A.2.1). One characteristic is the stove efficiency in % (Fig. A.10), which represents the ratio of energy used (i.e. "cooking energy delivered to pot") and the "total energy consumed". The total fuel consumption in DM given for the three phases of a WBT was also relevant in our analysis (Fig. A.10).

Note: Stoves like sawdust gasifiers, TLUD-microgasifiers, and biogas burners are often made out of metal sheets and bars. Steel has good thermal conductivity characteristics, which means that the material responds quickly to temperature differences (i.e. heating and cooling). Hence, differentiation between HP_hot and HP_cold is not required and WBTs were only conducted with HP_cold and LP for these stoves.

One can easily see that a three-stone-fire requires the highest **fuel consumption** in all phases, whereas the charcoal burner consumes the least fuel. A biogas burner is also characterised by comparably low fuel consumption. Comparing the analysed ICS, we can see that the rocket stove consumes less fuel in the later phases of cooking (i.e. HP_hot and LP). In contrast, the two microgasifier are more efficient in HP compared to LP-phases, which means less fuel is required during HP than in LP.

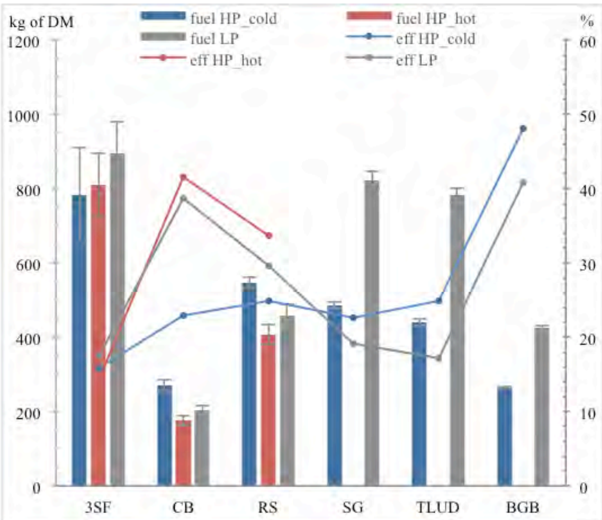


Fig. A.10: Results from the evaluation of collected WBT-data for selected stove technologies include (i) the fuel use in kg of DM (bar diagrams; left ordinate) and (ii) the efficiency (eff) in % (point diagrams; right ordinate); both values were assessed for the three phases HP_cold, HP_hot, and LP (see Section A.1.2); abbreviations of the stoves in Table A.2; plot data is provided in Table S.1.

Furthermore, a three-stone-fire characteristically shows similar **efficiency** across all phases of the WBT, whereas charcoal burner and rocket stove show lower efficiency when the stove is still cold at HP_cold since the insulation bricks need to heat first. The highest efficiencies are found in biogas burner and charcoal burner (excluding HP_cold). However, these two technologies require preceding biomass conversion processes. Thus, resources are used during charcoal production (i.e. pyrolysis) and in biogas digesters (i.e. anaerobic fermentation) to provide fuel for the stoves.

So, to evaluate the total efficiency of these cooking technologies, the efficiencies of pyrolysis and fermentation must be included. For our model, we took this into account by estimating and evaluating the total resource consumption in addition to the fuel consumption.

On average, the **cooking power** during the LP-phase was comparable for all stoves due to the standardized procedure for the WBT (i.e. defined size of pot, amount of water, simmering time, etc.). Microgasifier stoves and biogas burner are characterized by a higher cooking power during the HP-phase compared to the LP-phase. The cooking power of sawdust gasifier, TLUD, and biogas burner during the HP was high compared to the cooking power of three-stone-fire, charcoal burner, and rocket stove, when cooking started with a cold stove (HP_cold), and was comparable, when cooking with a hot stove (HP_hot). Especially for charcoal burner and rocket stove, the cooking power was highest during HP_hot.

Since heating up the insulation bricks and stones requires additional energy, three-stone-fire, charcoal burner, and rocket stove are characterized by a longer **time-to-boil** than sawdust gasifier, TLUD, and biogas burner, if the cooking starts with a cold stove. Nevertheless, the time-to-boil of three-stone-fire, charcoal burner, and rocket stove during HP_hot is comparable to the other stoves and was on average ≈ 22.6 minutes (for all stoves).

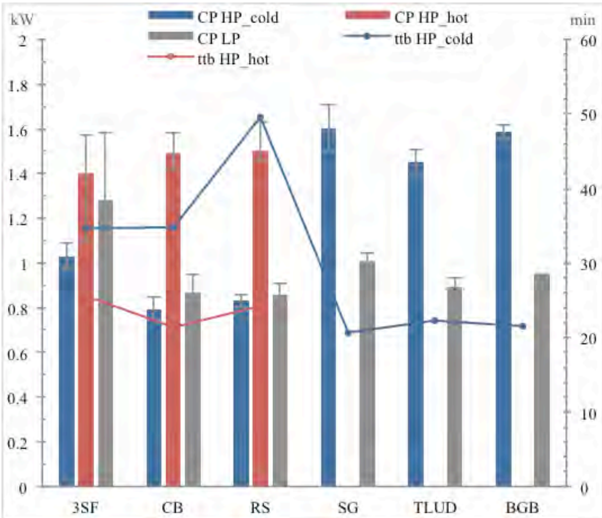


Fig. A.11: Results from evaluating collected WBT-data for selected stove technologies include (i) the average cooking power (CP) in kW (bar diagrams; left ordinate) and (ii) the corrected time-to-boil (ttb) in minutes (point diagrams; right ordinate); both values were assessed for the three phases HP_cold, HP_hot, and LP (see Section A.1.2); abbreviations of the stoves in Table A.2; plot data is provided in Table S.2.

To sum up, the results of the WBT-data evaluation indicate:

- **Microgasifiers** and **biogas stoves** had a higher efficiency and cooking power during the HP-phase compared to the LP- phase. Hence, these stoves are especially suitable for **fast and quick cooking** (e.g. boiling water for drinking, making tea, cooking vegetables, deep-frying so-called *mandazi*, etc.).
- On the other hand, especially **rocket stove, charcoal burner, and biogas burner** are appropriate when **cooking for a longer time**, because of their higher efficiency during simmering phases (e.g. beans, chickpeas, etc.).
- The possible **reduction of fuel consumption when using sawdust gasifier or TLUD** as compared to the three-stone-fire depends on the combination of HP- and LP-phases, which characterises the cooking process. Since fuel consumption is lower in the HP-phase than in LP-phases, short-term cooking has **more potential to reduce fuel consumption** than cooking with long simmering has (e.g. boiling water for tea or drinking water *versus* cooking beans for two hours).
- However, once packed with fuel and lightened, especially the sawdust gasifier shows a long firing duration, so that the cook can continue using the stove for a long period (e.g. up to more than two hours). Grimsby et al. (2016) observed similar cooking habits when using sawdust gasifier stoves in other regions of TZ.

We acknowledge that the WBT simplifies the real-life cooking conditions. A WBT is conducted in a very precise manner, so that the fire in the stove is stopped immediately after the LP-phase has terminated and the remaining fuel is removed from the stove. In real life however, the fire would keep going at least until all firewood, charcoal or sawdust is used up. Depending on the cook, it is likely that the heat is further used, e.g. for warming water to clean the dishes or for bathing, or that the stove is just set aside. In reality, it is also common to keep the stove at a low power for the whole day to maintain the glow for further cooking or to constantly warm water. Hence, we simplified the real-life scenario by assuming a defined cooking habit of using the stove exactly two times per day. Nevertheless, the results we derived from the MES-mode may well be considered an estimation of the minimum energy and resource demand of one family.

When evaluating the collected WBT-data, we observed that the quantities of residues available after cooking were only recorded in a few cases. This confirms the importance of our objective, namely to quantify these waste flows and to estimate the recycling potential to the agroecosystem. For example, ashes and biochar could be added to the compost and biogas slurry could directly be used as a fertilizer. Hence, contained nutrients could be recovered for agriculture.

Table A.8: Summary of sources for the collection of WBT-data with the total sample size (n) of the data set for each stove.

Alternative	Analysed technology	Fuel	References for the WBT-data
E1	Three-stone-fire	Firewood	EfCoiTa, 2014; Jetter and Kariher, 2009; (n = 4)
E2.2.	Charcoal burner	Charcoal	CREEC, 2015; EfCoiTa, 2014; Jetter and Kariher, 2009; (n = 13)
E3	Rocket stove	Firewood	CREEC, 2014; EfCoiTa, 2014; (n = 5)
E4	Sawdust gasifier	Sawdust	CREEC, 2014; EfCoiTa, 2014; (n = 6)
E5	Top-Lit UpDraft gasifier	Firewood	Awemu, 2014; CREEC, 2015; EfCoiTa, 2014; Jetter and Kariher, 2009; (n = 8; mixed for designs Mwoto, Troika, and Quad*)*
E6.2.	Biogas burner	Biogas	Barfuss, 2013; Khandelwal and Gupta, 2009; Schrecker, 2014; Tumwesige and Amaguru-Togboa, 2013; (n = 19)

A.4.2. Collected data used to characterize the analysed biogas digester

By accessing and evaluating data from the pilot operation of the BiogaST-digester, we could characterise the analysed digester. Within the case study, we collected data from August 2012 until November 2014, mainly on a daily base. For comparison, we collected data from other digesters built and used in TZ, which were investigated by Gyalpo (2010) and Vögeli et al. (2014) (Table A.9).

Table A.9: Summary from evaluation of data collected during pilot operation of the BiogaST-digester from 2012–2014 in Karagwe (case study), compared to average performances of digesters in TZ as found in literature.

		Case study:			Literature:			
Parameter	Unit	Mean	Error	n	Mean	Error	n	References
Daily feeding	kg FM d^{-1}	32.5	± 0.7	820	7.0	± 3.3	4	Gyalpo, 2010; Vögeli et al., 2014
Daily feeding	kg VS d^{-1}	4.2	± 0.9	calc.	2.8	± 1.1	2	Gyalpo, 2010; Vögeli et al., 2014
OLR	kg VS m^{-3} d^{-1}	0.4	± 0.1	calc.	0.6	± 0.2	4	Gyalpo, 2010; Vögeli et al., 2014
Daily gas production*	m^3 d^{-1}	0.65	± 0.02	743	0.7	± 0.3	4	Gyalpo, 2010; Vögeli et al., 2014
GPR	m^3 m^{-3} d^{-1}	0.06	± 0.02	calc.	0.30	± 0.07	4	Gyalpo, 2010; Vögeli et al., 2014
SGP_real	m^3 kg^{-1} VS	0.16	± 0.03	calc.	0.59	± 0.11	4	Gyalpo, 2010; Vögeli et al., 2014
SGP_real	m^3 kg^{-1} FM	0.02	± 0.04	calc.	0.098	± 0.001	2	Gyalpo, 2010

* The daily gas production excludes biogas losses, i.e. biogas consumed after leakages;
Abbreviations: calc.: values were *calc*ulated; GPR: gas production rate; n: number/size of data set; OLR: organic loading rate; SGP: specific gas production; VS: volatile substances.

In comparison to the literature references, the daily input of substrates to the BiogaST-digester was much higher, but led to a comparable daily gas production. The organic loading rate (OLR) was comparable to literature (≈ 65 % of OLR from reference studies) even though daily feeding of VS was higher in the case study. The fermenter in the BiogaST-design also has a bigger reactor volume as in the other fermenter types. Nevertheless, the gas production, either expressed as gas production rate (GPR, i.e. daily gas production in m^3 per unit reactor volume in m^3) or as material SGP (i.e. total gas production per mass of either total FM or total VS) was rather low in the case study. With GPR and SGP of the BiogaST-digester of 20 % and 25 %, respectively, of the performance of other digesters in TZ, the productivity of the pilot digester was low.

Some reasons for the comparatively poor performance of the BiogaST-digester might include:

- The average temperature in the fermenter was low (≈ 19–24° C), which lowered the gas production since fermentation only took place in the lower mesophilic range.
- The potential SGP of the agricultural residues as feeding substrate is lower than that of kitchen waste, which was used in the reference digesters.
- Undetected leakages could have caused high losses of biogas, so that the measurable gas production (after losses) was much lower than the total gas production (before losses).

Nevertheless, the collected data allowed modelling the biogas-system. Since this BiogaST-digester is still under development, we accounted for the **level of technological maturity** by implementing two sub-alternatives for the biogas system: one using the data derived from the pilot operation ("real" scenario) and the other using estimated parameters for improved performance ("ideal" scenario) (see section A.2.1 III, p. 6). However, the "ideal" SGP of roughly 0.29 m^3 kg^{-1} of VS, which was estimated from the specific potentials of the biomasses used in E6, still only makes up ≈ 50 % of the SGP reached in other cases in TZ.

When discussing the results of estimated resource consumption to operate a biogas digester, with respect to the size of land or number of cows, which are required for providing sufficient $\dot{m}_{input}$ to the biogas digester, we took the following assumption pursuant to literature:

- Residues from banana plants are 0.92 kg of DM m^{-2} yr^{-1} (Yamaguchi and Araki, 2004);
- Daily dung production of 17.5 kg of FM per cow – deduced from
  - a daily excretion of FM equal to 5 % of the living weight of the animal (Sasse, 1984) and
  - an average weight of 350 kg cow^{-1} in Karagwe (Becker, 2008).

Furthermore, when comparing the GHG-emissions from the biogas digester in the 'real world' model (based on pilot operation) and 'ideal world' model (improved digester performance), we observed the following trend: the higher the gas production, the lower the relative contribution of GHG-emissions from storing biogas slurry and the higher the relative contribution of GHG-emissions from biogas leaching. Our explanation for this relation is that a better performance of the digester requires lower input flows of materials to produce the same amount of biogas, i.e. meet the household's need. Therefore, less biogas slurry is produced and the emissions from storage of that slurry are also lower, whereas biogas leaching remains the same.

A.4.3. Plausibility criteria

As part of the data evaluation, we chose a set of plausibility criteria for crosschecking estimated values from our model with reliable data from literature sources (Table A.10). We discuss this comparison of the results from our model with the plausibility criteria in the main manuscript (Section 4.1.).

Table A.10: List of plausibility criteria used for evaluation of estimated results from system analysis (values in Table A.12).

Alternative	Criteria	Source
all	total energy consumed	O'Sullivan and Barnes, 2007
all	energy delivered to cooking pot	Hager and Morawicki, 2013
E1-E5	resource consumption/fuel demand	Akbar et al. (2011) provided values for East Africa, and O'Sullivan and Barnes (2007) estimated final fuel consumption for households in so-called "developing" countries based on energy delivered to the cooking pot.
E6	fuel demand	Rajendran et al., 2012; Vögeli et al., 2014
E6	biogas composition	Gyalpo, 2010; Lansing et al., 2008; Schrecker, 2014; Vögeli et al., 2014; Zhang et al., 2007
E4, E5	wood gas composition	Plis et al., 2011
E1, E3-E6	GHG-emissions	Smith et al. (2000) provided ultimate emission factors of pollutant mass per unit energy delivered to the cooking pot.
E1, E3-E6	GHG-emissions: comparison with other energy carriers	Atlantic consulting, 2009
E6	N and P content in biogas slurry	Gyalpo, 2010; Vögeli et al., 2014; Zirkler, 2015
E6	C content in biogas slurry	Gyalpo, 2010; Wendland, 2008

When crosschecking estimated results with literature for plausibility check, we found that the total energy consumption and the energy delivery to the cooking pot (Table S.4), which represented the functional unit of the MES in figures, were 18.2 ± 0.6 and 4.3 ± 0.2 GJ hh^{-1} yr^{-1} (average E1-E6), respectively. Our results are generally consistent with the literature (Hager and Morawicki, 2013; O'Sullivan and Barnes, 2007).

Furthermore, the composition of biogas as deduced from BiogaST-data was consistent with the literature (e.g. Lansing, 2008; Zhang, 2007) and the calculated decomposition of biomass in the microgasifier stoves was comparable to the composition of wood gas as determined by Plis et al. (2011).

A.4.4. Uncertainty check of estimated results from modelling according to error propagation statistics

After modelling, most flows of the MES-model had a RU of less than 30 %. Thus, in general, the uncertainty of the MES-model can be classified as low according to Laner et al. (2013). But, there are some exceptions that show average (± 50 %) or high (> 90 %) uncertainty (Table A.11).

Table A.11: Annotated list of flows of MES with average or high uncertainty.

Alternative	Flow	RU	Comment
E1, E3	S in firewood	38 %	S is not an indicator element; RU for following flows (e.g. S in emissions, OD for S emissions) remained < 40%.
E2.1	Air demand (OD) for charcoal production, all layers	> 200 %	Not a highly relevant flows because air is not a scarce resource. Furthermore, RU of OD for specific emissions were in the range of 16-53 %. However, the sum of OD was calculated as a combination of addition and subtraction, which can result in high RU (i.e. inherent problem challenging error propagation statistics).
E2.1	Ash & brands, all layers	40–50 %	RU derived from literature review. Flow was not of particular interest for our work, as these residues will not be considered a recycling flow. However, when assessing total environmental impacts of energy technologies, these emissions upon charcoal production on-site can be relevant.
E4	P in sawdust	37 %	Data providing concentration of P in energy carriers was hard to find since this is not an element crucial for energy conversion. However, it was of certain interest in our study to consider by-products for recycling. We put high efforts into data collection for this value and this was the best certainty we could reach. Impacts on other flows remain appropriate.
E4, E5	Moisture in char	40 %	Values varied through literature because the time of sampling plays a crucial role when determining this parameter. In general, directly after cooking, moisture should be around 0. Afterwards, moisture can increase as the matter absorbs water in the air. The RU in moisture effected RU of elemental composition in chars based on FM. However, here, RU was still moderate with < 50%.
E4*	C in wood gas next morning	67 %	Here, RU rose simply because it derived from a subtraction of values (i.e. limits of error propagation statistics; see above).
E4.2*, E5.2*	Emissions, AirIn and AirOur, all layers	50–80 %	Elevated RUs were generally acceptable here as these flows are not highly relevant since air is not a limited resource. RU was highest for N in import and export airflows, resulting from subtraction (see above).
E6.1	Biomass required, i.e. Resource input	30–40 %	Mean values were calculated from many factors involved in a fraction term. Nevertheless, RU was still moderate with <50 %.
E6.1	Biogas slurry removed and recycled; Biogas slurry overflow	40–50 %; >100 %	Material flows of removed and recycled slurry showed acceptable RUs of < 50 %. However, the flow of slurry, which left the digester via overflow, was calculated from balancing all input and output flows of the digester. Hence, it was a result of mixed addition and subtraction, causing high RU. Nevertheless, in the pilot project, it was difficult to quantify this flow. Thus, the high RU somehow matches reality in expressing high uncertainty about the quantity of this flow. Further research including data collection and material analysis could contribute to improving certainty on this flow.
E6.1	Emissions from storage	45–80 %	Emissions from storage depended on the amount of biogas slurry going through the outlet of the digester. Hence, RU of emissions followed RU of biogas slurry flows (see above). However, results are still adequate with RU < 90 %.

A.5. COLLECTED DATA

To determine the mean values of material characteristics and process parameters, we collected data from:

- Literature review.
- Project data of case studies including:
  - WBT-experiments conducted by EfCoiTa-team (A. Berten, F. Lorbach, A. Ndibarema, and F. Schmid) in Karagwe, 2013 and 2014;
  - Data collected by BiogaST-team (P. Becker, A. Bitakwate, K. Bremert, C. Clausnitzer, K. Simon, and others) during test operation of a pilot digester from 2012–2014 in Chonyonyo, Karagwe;
  - Soil and material samples collected and analysed in the CaSa-project (J. Alexander, I. Bamuhiga, A. Bitakwate, J. Geffers, A. Krause, D. Vedasto, and others) from 2012–2014.
- Sampling of materials and analysis in laboratory, including:
  - Experiments conducted by A. Krause and F. Schmid in Karagwe, 2014 (Section A.2.2.II).
  - Laboratory analysis conducted at TU Berlin (department of soil science) with various samples taken in Karagwe by A. Krause from 2010-2014.

Table A.12: List of material characteristics and other parameter values for the MES-model, obtained from data collection and literature review.

Name	Unit	$\bar{x}$	Δx	RU	n	Sources	Comments	Spatial context
						Moisture content		
Firewood	% FM	0.121	± 0.003	2 %	26	Barfuss et al., 2013; Bhattacharya et al., 2002; CREEC, 2015; Jetter and Kariher, 2009	Literature review (19), experiments EfCoiTa, 2014 (7)	Asia, Ethiopia, Karagwe, Uganda
Charcoal	% FM	0.050	± 0.002	4 %	10	Bhattacharya et al., 2002; CaSa, 2015; Jetter and Kariher, 2009; Pennise et al., 2001	Literature review	Asia, Karagwe, Kenya
Sawdust	% FM	0.113	± 0.003	3 %	34	Barfuss et al., 2013; Bhattacharya et al., 2002; CaSa, 2015; CREEC, 2014; CREEC, 2015; Dixit et al., 2006; Jetter and Kariher, 2009; Venkataraman et al., 2004	Literature review (30), experiments EfCoiTa, 2014 (4)	Asia, Ethiopia, India, Karagwe, Uganda
Ash and char	% FM	0.037	± 0.014	37 %	12	McLaughlin et al., 2009	Literature review	USA
Banana stem	% FM	0.897	± 0.002	0 %	6	Becker, 2008	Literature review (4), Sampling and analysis, 2014 (2)	Karagwe
Cow dung	% FM	0.781	± 0.023	3 %	7	Barfuss et al., 2013; Becker, 2008; CaSa, 2015; Rajendran et al., 2012	Literature review (5), Sampling and analysis, 2014 (2)	Ethiopia, Karagwe
Biogas slurry	% FM	0.958	± 0.012	1 %	9	Barfuss et al., 2013; Becker, 2008; CaSa, 2015; Vögeli et al., 2014	Literature review (7), Sampling and analysis, 2014 (2)	Ethiopia, Karagwe, TZ
						Ash content		
Firewood	% DM	0.015	± 0.002	14 %	15	Reed and Gaur, 1998; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Okorio, 2006	Literature review	Austria, Germany, Kagera, South Africa, Uganda
Charcoal	% DM	0.034	± 0.004	13 %	51	Reed and Gaur, 1998; Girard, 2002; IBI data base, 2015; Kloss et al., 2012; Pastor-Villegas et al., 2006	Literature review (11), IBI data base (40)	Austria, Spain, Togo
Sawdust	% DM	0.015	± 0.002	16 %	21	Basu, 2010; Dixit et al., 2006; Reed and Gaur, 1998; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Okorio, 2006; Venkataraman et al., 2004	Literature review	Austria, Germany, India, Kagera, South Africa, Uganda
Ash and char	% DM	0.033	± 0.007	21 %	12	McLaughlin et al., 2009	Literature review	USA
Banana stem	% DM	0.143	± 0.007	5 %	4	Becker, 2008	Literature review	Karagwe
Cow dung	% DM	0.143	± 0.003	2 %	2	Becker, 2008	Literature review	Karagwe
						Elemental concentrations from ultimate analysis		
H in:								
Firewood	% DM	0.064	± 0.001	2 %	14	Bhattacharya et al., 2002; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Asia, Austria, Germany, South Africa, USA
Charcoal	% DM	0.035	± 0.003	9 %	57	Reed and Gaur, 1998; IBI data base, 2015; Kloss et al., 2012; Pastor-Villegas et al., 2006	Literature review (6), IBI data base (51)	Austria, Spain
Sawdust	% DM	0.063	± 0.001	2 %	16	Basu, 2010; Bhattacharya et al., 2002; Dixit et al., 2006; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Asia, Austria, Germany, India, South Africa, USA
Ash and char	% DM	0.033	± 0.002	7 %	12	McLaughlin et al., 2009	Literature review	USA

O in:								
Firewood	% DM	0.422	± 0.005	1 %	13	Bhattacharya et al., 2002; Kaltschmitt et al., 2009; Munalula and Meincken, 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Asia, Germany, South Africa, USA
Charcoal	% DM	0.158	± 0.015	10 %	55	Bhattacharya et al., 2002; IBI data base, 2015; Pastor-Villegas et al., 2006; Reed and Gaur, 1998	Literature review (4), IBI data base (51)	Asia, Spain
Sawdust	% DM	0.432	± 0.007	2 %	15	Basu, 2010; Bhattacharya et al., 2002; Dixit et al., 2006; Reed and Gaur, 1998; Kaltschmitt et al., 2009; Munalula and Meincken, 2009; Ragland and Aerts, 1991	Literature review	Asia, Germany, India, South Africa, USA,
Ash and char	% DM	0.152	± 0.011	7 %	12	McLaughlin et al., 2009	Literature review	USA
C in:								
Firewood	% DM	0.489	± 0.007	1 %	20	Bhattacharya et al., 2002; Girard, 2002; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Okorio, 2006; Pennise et al., 2001; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Asia, Austria, Germany, Kagera, Kenya, South Africa, Togo, Uganda, USA
Charcoal	% DM	0.735	± 0.011	1 %	75	Bhattacharya et al., 2002; CaSa, 2015; Girard, 2002; Granatstein et al., 2009; IBI data base, 2015; Kloss et al., 2012; Lehmann and Joseph, 2009; Pastor-Villegas et al., 2006; Pennise et al., 2001; Reed and Gaur, 1998	Literature review (24), IBI data base (51)	Asia, Austria, Karagwe, Kenya, Spain, Togo, USA
Sawdust	% DM	0.488	± 0.004	1 %	26	Basu, 2010; Bhattacharya et al., 2002; CaSa, 2015; Dixit et al., 2006; Girard, 2002; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Okorio, 2006; Pennise et al., 2001; Ragland and Aerts, 1991; Reed and Gaur, 1998; Venkataraman et al., 2004	Literature review (25), Sampling and analysis, 2014 (1)	Austria, Germany, Asia, Kagera, Karagwe, Kenya, South Africa, Togo, Uganda, USA
Ash and char	% DM	0.780	± 0.020	3 %	12	McLaughlin et al., 2009	Literature review	USA
Ash & char SG*	% DM	0.501	± 0.058	12 %	2		Sampling and analysis, 2014	Karagwe
Ash & char TLUD*	% DM	0.281	± 0.076	27 %	2		Sampling and analysis, 2014	Karagwe
Banana stem	% DM	0.385	± 0.002	0 %	2	Bilba et al., 2007	Literature review (1), Sampling and analysis, 2014 (1)	Guadeloupe, Karagwe
Cow dung	% DM	0.389	± 0.011	3 %	3	Barfuss et al., 2013	Literature review (2), Sampling and analysis, 2014 (1)	Ethiopia, Karagwe
Biogas slurry	% DM	0.389	± 0.032	8 %	6	CaSa, 2015; Vögeli et al., 2014	Literature review (5), Sampling and analysis, 2014 (1)	Karagwe, TZ
N in:								
Firewood	% DM	0.003	± 0.001	16 %	14	Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Austria, Germany, South Africa, USA

Charcoal	% DM	0.004	± 0.001	14 %	69	CaSa, 2015; Granatstein et al., 2009; IBI data base, 2015; Kloss et al., 2012; Lehmann and Joseph, 2009; Pastor-Villegas et al., 2006; Reed and Gaur, 1998; Taylor, 2010	Literature review (18), IBI data base (51)	Austria, Karagwe, Spain, USA
Sawdust	% DM	0.003	± 0.0005	19 %	21	Basu, 2010; CaSa, 2015; Dixit et al., 2006; Kaltschmitt et al., 2009; Kloss et al., 2012; Munalula and Meincken, 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998; Taylor, 2010; Venkataraman et al., 2004	Literature review (20), sampling and analysis, 2014 (1)	Austria, Germany, India, Karagwe, South Africa, USA
Ash and char	% DM	0.003	± 0.0001	3 %	15	CaSa, 2015; McLaughlin et al., 2009	Literature review (13), sampling and analysis, 2014 (2)	Karagwe, USA
Banana stem	% DM	0.009	± 0.00003	0 %	2	Bilba et al., 2007	Literature review (1), sampling and analysis, 2014 (1)	Guadeloupe, Karagwe
Cow dung	% DM	0.017	± 0.001	6 %	4	Barfuss et al., 2013; CaSa 2012	Literature review (2), sampling and analysis, 2014 (2)	Ethiopia, Karagwe
Biogas slurry	% DM	0.029	± 0.007	26 %	5	CaSa, 2015; Vögeli et al., 2014	Literature review (3), sampling and analysis, 2014 (2)	Karagwe, TZ
S in:								
Firewood	% DM	0.0004	± 0.0001	38 %	8	Kaltschmitt et al., 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review	Germany, USA
Charcoal	% DM	0.0003	± 0.0001	27 %	11	Granatstein et al., 2009; Pastor-Villegas et al., 2006; Reed and Gaur, 1998	Literature review (11)	Spain, USA, others
Sawdust	% DM	0.001	± 0.0001	10 %	10	CaSa,2012; Kaltschmitt et al., 2009; Ragland and Aerts, 1991; Reed and Gaur, 1998	Literature review (9) & sampling and analysis, 2014 (1)	Germany, Karagwe, USA
P in:								
Firewood	% DM	0.001	± 0.0002	27 %	4	Kaltschmitt et al., 2009	Literature review	Germany
Charcoal	% DM	0.002	± 0.002	78 %	16	IBI data base, 2015; Lehmann and Joseph, 2009;	Literature review	
Sawdust	% DM	0.0004	± 0.0001	20 %	7	Kaltschmitt et al., 2009; Uckert, 2004;	Literature review (5), sampling and analysis, 2014 (2)	Germany, Karagwe
Banana stem	% DM	0.001	± 0.00001	1 %	1		sampling and analysis, 2014	Karagwe
Cow dung	% DM	0.004	± 0.0001	2 %	1		sampling and analysis, 2014	Karagwe
Biogas slurry	% DM	0.038	± 0.003	9 %	4	Vögeli et al., 2014	Literature review (2), Sampling and analysis, 2014 (2)	Karagwe, TZ
Concentration of volatile matter								
Firewood	% DM	0.840	NA	NA		Barfuss et al., 2013	Literature review	Ethiopia
Charcoal	% DM	0.406	± 0.036	9 %	31	Data base IBI	Literature review	others
Sawdust	% DM	0.698	± 0.041	6 %	2	Dixit et al., 2006; Venkataraman et al., 2004	Literature review	
Ash and char	% DM	0.095	± 0.009	10 %	12	McLaughlin et al., 2009	Literature review	USA
Net calorific value								
Firewood	MJ kg^{-1}	17.9	± 0.3	2 %	19	Barfuss et al., 2013; CREEC, 2014; EfCoiTa, 2014; Jetter and Kariher, 2009; Kaltschmitt et al., 2009; Kumar and Gupta, 1992; Munalula and Meincken, 2009; Pennise et al., 2001; Sanga and Jannuzzi, 2005; Sasse, 1987; Visser, 2005	Literature review	Ethiopia, Germany, Karagwe, Kenya, South Africa, TZ, USA
Charcoal	MJ kg^{-1}	28.2	± 1.5	5 %	10	Jetter and Kariher, 2009; Pennise et al., 2001; Sanga and Jannuzzi, 2005; Visser, 2005	Literature review	India, Kenya, TZ, USA

Sawdust	MJ kg^{-1}	17.6	± 0.3	2 %	21	Bhanap and Deshmukh, 2012; Barfuss et al., 2013; CREEC, 2014; EfCoiTa, 2014; Jetter and Kariher, 2009; Kaltschmitt et al., 2009; Kumar and Gupta, 1992; Munalula and Meincken, 2009; Pennise et al., 2001; Sanga and Jannuzzi, 2005; Sasse, 1987; Visser, 2005	Literature review	Ethiopia, Germany, India, Karagwe, Kenya, South Africa, TZ, USA
Biogas	MJ kg^{-1}	19.2	± 1.0	5 %	5	Barfuss et al., 2013; Khandelwal and Gupta, 2009; Schrecker, 2014	Literature review (4), Own calculation (1)	Ethiopia, Germany, Karagwe, Kenya, South Africa, TZ, USA
Charcoal production								
Efficiency	% DM	0.238	± 0.026	11 %	11	Adam, 2009; Malimbwi and Zahabu, 2009; Msuya et al., 2011; Pennise et al., 2001	Literature review	East Africa, Kenya, TZ
Solid products	% DM	0.316	± 0.028	9 %	7	Msuya et al., 2011; Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya, TZ
Ash and brands products	% DM	0.052	± 0.024	45 %	6	Kim Oanh et al., 1999; Pennise et al., 2001	Literature review	Asia, Kenya
Charcoal products	% DM	0.232	± 0.028	12 %	15	Adam, 2009; Kammen and Lew, 2005; Malimbwi and Zahabu, 2009; Msuya et al., 2011; Pennise et al., 2001	Literature review	East Africa, Kenya, TZ
Gas products	% DM	0.531	± 0.049	9 %	7	Msuya et al., 2011; Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya, TZ
Water products	% DM	0.154	± 0.014	9 %	2	Msuya et al., 2011; Lehmann and Joseph, 2009	Literature review	TZ
Non-water liquid prod	% DM	0.121	± 0.011	9 %	2	Msuya et al., 2011; Lehmann and Joseph, 2009	Literature review	TZ
C in non water liquids	% FM	0.609	NA	NA	1	Williams and Besler, 1996	Literature review	UK
H in non water liquids	% FM	0.093	NA	NA	1	Williams and Besler, 1996	Literature review	UK
O in non water liquids	% FM	0.282	NA	NA	1	Williams and Besler, 1996	Literature review	UK
CO_2 emissions	g kg^{-1}	1802	± 354	20 %	5	Pennise et al., 2001	Literature review	Kenya
CO emissions	g kg^{-1}	208	± 24	12 %	7	Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya
CH_4 emissions	g kg^{-1}	46	± 4	9 %	7	Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya
TNMHC emissions	g kg^{-1}	75	± 14	19 %	7	Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya
NO_x emissions	g kg^{-1}	0.06	± 0.02	31 %	5	Pennise et al., 2001	Literature review	Kenya
PM emissions	g kg^{-1}	135	± 81	60 %	7	Lehmann and Joseph, 2009; Pennise et al., 2001	Literature review	Kenya
Production of ash and char when using microgasifier stoves								
TLUD	% FM	0.200	± 0.011	6 %	27	Andreatta, 2007; CREEC, 2015; EfCoiTa, 2014; Lehmann and Joseph, 2009; Roth, 2011	Literature review (24), Sampling and analysis, 2014 (3)	Karagwe, Uganda, USA, others
SG	% FM	0.213	± 0.019	9 %	26	Andreatta, 2007; CREEC, 2015; EfCoiTa, 2014; Lehmann and Joseph, 2009; Roth, 2011	Literature review (24), Sampling and analysis, 2014 (2)	Karagwe, Uganda, USA, others
TLUD*	% FM	0.054	± 0.011	20 %	2		Sampling and analysis,	Karagwe
SG*	% FM	0.128	± 0.040	31 %	2		Sampling and analysis,	Karagwe
Organic wastes for fermentation (kitchen, market, canteen): elemental concentrations and biogas production potential								
DM	% FM	0.110	± 0.056	51 %	6	Gyalpo, 2010; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, TZ
Moisture content	% FM	0.898	± 0.051	6 %	6	Gyalpo, 2010; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, TZ
VS	% DM	0.917	± 0.018	2 %	6	Gyalpo, 2010; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, TZ
Total C	% DM	0.491	± 0.024	5 %	2	Gyalpo, 2010; Zhang et al., 2007	Literature review	China, TZ
Total N	% DM	0.032	NA	NA	1	Gyalpo, 2010;	Literature review	TZ

Total P	% DM	0.005	NA	NA	1	Zhang et al., 2007	Literature review	China
SGP_ideal Banana stem	$m^3\ kg^{-1}$ VS	0.3	NA	NA	1	Knaebel, 2006	Literature review	Cuba
SGP_ideal Cow dung	$m^3\ kg^{-1}$ VS	0.3	NA	NA	1	Knaebel, 2006	Literature review	Cuba
Banana residues	kg DM $m^{-2}\ yr^{-1}$	0.92	NA	NA	1	Yamaguchi und Araki, 2004	Literature review	TZ
Dung production of cows in FM	% of cow's living weight d^{-1}	0.05	NA	NA	1	Sasse, 1984	Literature review	
Bulk density Biogas slurry	kg FM dm^{-3}	1.000	± 0.000	0 %	4	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
				Emissions from biogas system				
Leakages	vol.- %	0.185	± 0.013	19 %	2	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
Emissions from storage:								
CH_4	g m^{-3}	1026	± 308	30 %	2	Amon et al., 2006; Wang et al., 2014	Literature review	Austria, China
CO_2	g m^{-3}	1586	± 476	30 %	1	Wang et al., 2014	Literature review	China
N_2O	g m^{-3}	14.5	± 4.4	30 %	2	Amon et al., 2006; Wang et al., 2014	Literature review	Austria, China
NH_3	g m^{-3}	79	± 24	30 %	2	Amon et al., 2006; Wang et al., 2014	Literature review	Austria, China
NO	g m^{-3}	negligible			1	Wang et al., 2014	Literature review	China
N losses during digestion	g m^{-3}	negligible			1	Clemens et al., 2006	Literature review	
SGP_real	$m^3\ kg^{-1}$ FM	0.1	± 0.001	1 %	2	Gyalpo, 2010	Literature review	TZ
				Plausibility criteria				
Resource consumption when using:								
Three-stone-fire	kg $hh^{-1}\ yr^{-1}$	1569	± 231	15 %	2	Akbar et al., 2011; O'Sullivan and Barnes, 2007		
Charcoal burner	kg $hh^{-1}\ yr^{-1}$	763	± 125	16 %	2	Akbar et al., 2011; O'Sullivan and Barnes, 2007		
Charcoal burner (efficient)	kg $hh^{-1}\ yr^{-1}$	541	± 119	22 %	2	Akbar et al., 2011; O'Sullivan and Barnes, 2007		
Improved wood stove	kg $hh^{-1}\ yr^{-1}$	1374	± 294	21 %	2	Akbar et al., 2011; O'Sullivan and Barnes, 2007		
Biogas	kg $hh^{-1}\ yr^{-1}$	317	NA		1	O'Sullivan and Barnes, 2007		
Biogas consumption	$m^3\ h^{-1}$	0.363	± 0.061	36 %	2	Rajendran et al., 2012; Vögeli et al., 2014	Literature review	TZ, others
Biogas composition:								
CH_4 in biogas	vol.- %	61.8	± 3.9	6 %	5	Gyalpo, 2010; Lansing et al., 2008; Schrecker, 2014; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, Germany, TZ
CO_2 in biogas	vol.- %	34.3	± 3.8	11 %	4	Gyalpo, 2010; Lansing et al., 2008; Schrecker, 2014; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, Germany, TZ
O_2 in biogas	vol.- %	0.8	± 0.4	47 %	3	Gyalpo, 2010; Lansing et al., 2008; Schrecker, 2014; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, Germany, TZ
H_2S in biogas	ppm	2598	± 2471	95 %	4	Gyalpo, 2010; Lansing et al., 2008; Schrecker, 2014; Vögeli et al., 2014; Zhang et al., 2007	Literature review	China, Germany, TZ
Characteristics of biogas slurry:								
DM	% FM	0.004	± 0.000	8 %	4	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
VS	% DM	0.493	± 0.021	4 %	4	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
Total N	% DM	0.064	± 0.010	16 %	4	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
Total P	% DM	0.014	± 0.003	25 %	4	Gyalpo, 2010; Vögeli et al., 2014	Literature review	TZ
Total C	% DM	0.399	± 0.104	26 %	20	Literature review by Zirkler et al., 2014	Literature review	Europe
Total N	% DM	0.076	± 0.060	79 %	20	Literature review by Zirkler et al., 2014	Literature review	Europe
Total P	% DM	0.011	± 0.060	55 %	20	Literature review by Zirkler et al., 2014	Literature review	Europe

A.6. LIST OF PROCESSES AND FLOWS

Table A.13: List of processes (PR), sub-processes and flows as implemented in STAN for six MES-alternatives (E1 to E6)

	Process	Flow	Flow name	Source process	Destination process
Alternative E1: 3SF					
PR: 3SF					
Input	PR1	F1	Firewood	IMPORT	PR1,3SF
	PR1	AirIn1	Air demand	IMPORT	PR1,3SF
Output	PR1	AirOut1	Air out	PR1,3SF	EXPORT
	PR1	Em1	Emissions	PR1,3SF	EXPORT
	PR1	Res1	Ash	PR1,3SF	EXPORT
Alternative E2: CP + CB					
PR: CP					
Input	PR2.1	AirIn2.1	Air demand	IMPORT	PR2.1, CP
	PR2.1	R2	Fuel wood	IMPORT	PR2.1, CP
Output	PR2.1	F2	Charcoal	PR2.1, CP	PR2.2, CB
	PR2.1	EmV2.1	Gaseous emissions	PR2.1, CP	EXPORT
	PR2.1	AirOut2.1	Air out	PR2.1, CP	EXPORT
	PR2.1	Res2.1	Ash & brands	PR2.1, CP	EXPORT
	PR2.1	EmL2.1	Liquid emissions	PR2.1, CP	EXPORT
PR: CB					
Input	PR2.2	F2	Charcoal	PR2.1, CP	PR2.2, CB
	PR2.2	AirIn2.2	Air demand	IMPORT	PR2.2, CB
Output	PR2.2	AirOut2.2	Air out	PR2.2, CB	EXPORT
	PR2.2	Em2.2	Emissions	PR2.2, CB	EXPORT
	PR2.2	Res2.2	Ash	PR2.2, CB	EXPORT
Alternative E3: RS					
PR: RS					
Input	PR3	F3	Firewood	IMPORT	PR3, RS
	PR3	AirIn3	Air demand	IMPORT	PR3, RS
Output	PR3	AirOut3	Air out	PR3, RS	EXPORT
	PR3	Em3	Emissions	PR3, RS	EXPORT
	PR3	Res3	Ash	PR3, RS	EXPORT
Alternative E4: SG					
PR: SG					
Input	PR4.1	AirIn4.1	Air demand	IMPORT	PR4.1, SG
	PR4.1	F4	Sawdust	IMPORT	PR4.1, SG
Output	PR4.1	Res4.1	Ash &char	PR4.1, SG	EXPORT
	PR4.1	Em4.1	Emissions	PR4.1, SG	EXPORT
	PR4.1	AirOut4.1	Air out	PR4.1, SG	EXPORT
Alternative E4*: SG					
PR: SG					
Input	PR4.1	AirIn4.1	Air demand	IMPORT	PR4.1, SG
	PR4.1	F4	Sawdust	IMPORT	PR4.1, SG
Output	PR4.1	Res4.1	Ash &char	PR4.1, SG	PR4.2, SG*
	PR4.1	Em4.1	Emissions	PR4.1, SG	EXPORT
	PR4.1	AirOut4.1	Air out	PR4.1, SG	EXPORT
PR: SG*					
Input	PR4.2	Res4.1	Ash &char	PR4.1, SG	PR4.2, SG*
	PR4.2	AirIn4.2	Air demand	IMPORT	PR4.2, SG*
Output	PR4.2	AirOut4.2	Air out	PR4.2, SG*	EXPORT
	PR4.2	Em4.2	Emissions	PR4.2, SG*	EXPORT
	PR4.2	Res4.2	Ash &char	PR4.2, SG*	EXPORT
Alternative E5: TLUD					
PR: TLUD					
Input	PR5.1	AirIn5.1	Air demand	IMPORT	PR5.1, TLUD
	PR5.1	F5	Firewood	IMPORT	PR5.1, TLUD
Output	PR5.1	Res5.1	Ash &char	PR5.1, TLUD	EXPORT
	PR5.1	Em5.1	Emissions	PR5.1, TLUD	EXPORT
	PR5.1	AirOut5.1	Air out	PR5.1, TLUD	EXPORT
Alternative E5*: TLUD					
PR: TLUD					
Input	PR5.1	AirIn5.1	Air demand	IMPORT	PR5.1, TLUD
	PR5.1	F5	Firewood	IMPORT	PR5.1, TLUD
Output	PR5.1	Res5.1	Ash &char	PR5.1, TLUD	EXPORT
	PR5.1	Em5.1	Emissions	PR5.1, TLUD	EXPORT
	PR5.1	AirOut5.1	Air out	PR5.1, TLUD	EXPORT
PR: TLUD *					
Input	PR5.2	Res5.1	Ash &char	PR5.1, TLUD	PR5.2, TLUD*
	PR5.2	AirIn5.2	Air demand	IMPORT	PR5.2, TLUD*
Output	PR5.2	AirOut5.2	Air out	PR5.2, TLUD*	EXPORT
	PR5.2	Em5.2	Emissions	PR5.2, TLUD*	EXPORT
	PR5.2	Res5.2	Ash &char	PR5.2, TLUD*	EXPORT
Alternative E6i: BGD ideal + BGB					
PR: BGD_ideal					
Input	PR6.1i	R6.1.1i	Banana stem	IMPORT	SPR6.1.1, Inlet: feeding
	PR6.1i	R6.1.2i	Cow dung	IMPORT	SPR6.1.1, Inlet: feeding

	Process	Flow	Flow name	Source process	Destination process
Output	PR6.1i	Em6.1i	Sum emissions	SPR6.1.5, Sum emissions	EXPORT
	PR6.1i	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
	PR6.1i	BS_Rem6.1i	Biogas slurry removed	SPR6.1.4, Outlet: slurry storage	EXPORT
	PR6.1i	BS_Ove6.1i	Biogas slurry overflow	SPR6.1.4, Outlet: slurry storage	EXPORT
SPR: Inlet, feeding					
Input	SPR6.1.1	R6.1.2i	Cow dung	IMPORT	SPR6.1.1, Inlet: feeding
	SPR6.1.1	R6.1.1i	Banana stem	IMPORT	SPR6.1.1, Inlet: feeding
	SPR6.1.1	BS_Rec6.1i	Biogas slurry recycled	SPR6.1.4, Outlet: slurry storage	SPR6.1.1, Inlet: feeding
Output	SPR6.1.1	R6.1i	Resource input total	SPR6.1.1, Inlet: feeding	SPR6.1.2, fermenter
SPR: fermenter					
Input	SPR6.1.2	R6.1i	Resource input total	SPR6.1.1, Inlet: feeding	SPR6.1.2, fermenter
Output	SPR6.1.2	F6.1	Biogas produced	SPR6.1.2, fermenter	SPR6.1.3, gas storage
	SPR6.1.2	BS6.1i	Biogas slurry sum	SPR6.1.2, fermenter	SPR6.1.4, Outlet: slurry storage
SPR: gas storage					
Input	SPR6.1.3	F6.1	Biogas produced	SPR6.1.2, fermenter	SPR6.1.3, gas storage
Output	SPR6.1.3	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
	SPR6.1.3	EmLec6.1	Biogas leaked	SPR6.1.3, gas storage	SPR6.1.5, Sum emissions
SPR: Outlet, slurry storage					
Input	SPR6.1.4	BS6.1i	Biogas slurry sum	SPR6.1.2, fermenter	SPR6.1.4, Outlet: slurry storage
Output	SPR6.1.4	EmSto6.1i	Emissions storage	SPR6.1.4, Outlet: slurry storage	SPR6.1.5, Sum emissions
	SPR6.1.4	BS_Rem6.1i	Biogas slurry removed	SPR6.1.4, Outlet: slurry storage	EXPORT
	SPR6.1.4	BS_Ove6.1i	Biogas slurry overflow	SPR6.1.4, Outlet: slurry storage	EXPORT
	SPR6.1.4	BS_Rec6.1i	Biogas slurry recycled	SPR6.1.4, Outlet: slurry storage	SPR6.1.1, Inlet: feeding
SPR: Sum emissions					
Input	SPR6.1.5	EmLec6.1	Biogas leaked	SPR6.1.3, gas storage	SPR6.1.5, Sum emissions
	SPR6.1.5	EmSto6.1i	Emissions storage	SPR6.1.4, Outlet: slurry storage	SPR6.1.5, Sum emissions
Output	SPR6.1.5	Em6.1i	Sum emissions	SPR6.1.5, Sum emissions	EXPORT
SPR: BGB					
Input	PR6.2	AirIn6.2	Air demand	IMPORT	PR6.2, BGB
	PR6.2	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
Output	PR6.2	AirOut6.2	Air out	PR6.2, BGB	EXPORT
	PR6.2	Em6.2	Emissions	PR6.2, BGB	EXPORT
Alternative E6i: BGD real + BGB					
PR: BGD_ideal					
Input	PR6.1r	R6.1.1r	Banana stem	IMPORT	SPR6.1.1, Inlet: feeding
	PR6.1r	R6.1.2r	Cow dung	IMPORT	SPR6.1.1, Inlet: feeding
Output	PR6.1r	Em6.1r	Sum emissions	SPR6.1.5, Sum emissions	EXPORT
	PR6.1r	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
	PR6.1r	BS_Rem6.1r	Biogas slurry removed	SPR6.1.4, Outlet: slurry storage	EXPORT
	PR6.1r	BS_Ove6.1r	Biogas slurry overflow	SPR6.1.4, Outlet: slurry storage	EXPORT
SPR: Inlet, feeding					
Input	SPR6.1.1	R6.1.2r	Cow dung	IMPORT	SPR6.1.1, Inlet: feeding
	SPR6.1.1	R6.1.1r	Banana stem	IMPORT	SPR6.1.1, Inlet: feeding
	SPR6.1.1	BS_Rec6.1r	Biogas slurry recycled	SPR6.1.4, Outlet: slurry storage	SPR6.1.1, Inlet: feeding
Output	SPR6.1.1	R6.1r	Resource input total	SPR6.1.1, Inlet: feeding	SPR6.1.2, fermenter

	Process	Flow	Flow name	Source process	Destination process
SPR: fermenter					
Input	SPR6.1.2	R6.1r	Resource input total	SPR6.1.1, Inlet: feeding	SPR6.1.2, fermenter
Output	SPR6.1.2	F6.1	Biogas produced	SPR6.1.2, fermenter	SPR6.1.3, gas storage
	SPR6.1.2	BS6.1r	Biogas slurry sum	SPR6.1.2, fermenter	SPR6.1.4, Outlet: slurry storage
SPR: gas storage					
Input	SPR6.1.3	F6.1	Biogas produced	SPR6.1.2, fermenter	SPR6.1.3, gas storage
Output	SPR6.1.3	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
	SPR6.1.3	EmLec6.1	Biogas leaked	SPR6.1.3, gas storage	SPR6.1.5, Sum emissions
SPR: Outlet, slurry storage					
Input	SPR6.1.4	BS6.1r	Biogas slurry sum	SPR6.1.2, fermenter	SPR6.1.4, Outlet: slurry storage
Output	SPR6.1.4	EmSto6.1r	Emissions storage	SPR6.1.4, Outlet: slurry storage	SPR6.1.5, Sum emissions
	SPR6.1.4	BS_Rem6.1r	Biogas slurry removed	SPR6.1.4, Outlet: slurry storage	EXPORT
	SPR6.1.4	BS_Ove6.1r	Biogas slurry overflow	SPR6.1.4, Outlet: slurry storage	EXPORT
	SPR6.1.4	BS_Rec6.1r	Biogas slurry recycled	SPR6.1.4, Outlet: slurry storage	SPR6.1.1, Inlet: feeding
SPR: Sum emissions					
Input	SPR6.1.5	EmLec6.1	Biogas leaked	SPR6.1.3, gas storage	SPR6.1.5, Sum emissions
	SPR6.1.5	EmSto6.1r	Emissions storage	SPR6.1.4, Outlet: slurry storage	SPR6.1.5, Sum emissions
Output	SPR6.1.5	Em6.1r	Sum emissions	SPR6.1.5, Sum emissions	EXPORT
SPR: BGB					
Input	PR6.2	AirIn6.2	Air demand	IMPORT	PR6.2, BGB
	PR6.2	F6.2	Biogas	SPR6.1.3, gas storage	PR6.2, BGB
Output	PR6.2	AirOut6.2	Air out	PR6.2, BGB	EXPORT
	PR6.2	Em6.2	Emissions	PR6.2, BGB	EXPORT

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A.8. LIST OF ABBREVIATIONS

AirIn	Input of air
AirOut	Output of air
Ash & char	Residues available after cooking with a microgasifier, i.e. a mix of ash and char particles
BiogaST	Project "Biogas Support for Tanzania"
C	Carbon
calc.	Calculated values
CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CHEMA	Programme for Community Habitat Environmental Management, a local NGO and project partner of the present research project
CREEC	Center for Research in Energy and Energy Conservation
DM	Dry matter
EfCoiTa	Project "Efficient Cooking in Tanzania"
eff	Efficiency
EM_{comb}	Emissions from combustion
EP	Eutrophication potential
EWB	Engineers Without Borders
F	Fuel demand
FM	Fresh matter
CO_{fac}	Defined "CO-factor"
frac	Mass fraction
$frac_{banana}$	Fraction of FM of banana stem
$frac_{cowdung}$	Fraction of FM of cow dung
$frac_{leakages}$	Fraction of biogas leakages
G	Goods
GHG	Greenhouse gas
GPR	Gas production rate
GWP	Global warming potential
H	Hydrogen
HH	Households
HP	"High Power"-phase
HP_cold	"High power with cold stove"
HP_hot	"High power with hot stove"
i	"Ideal" scenario
ICS	Improved cooking stoves
LP	"Low Power"-phase
$\dot{m}$	Material flow
MAVUNO	Swahili for "harvest", name of a local NGO and project partner of the present research project
MES	Micro energy system
MF	Model factor
MFA	Material flow analysis
n	Total sample size, i.e. number of replications
N	Nitrogen
NA	Not analysed
NGO	Non-governmental organisation
O	Oxygen
OD	Stoichiometric oxygen demand
OLR	Organic loading rate
P	Phosphorus
PEMS	Portable emissions monitoring system
PM	Particulate matter
$PM_{2.5}$	PM with a size of 2.5 µm
σ	Standard deviation
ρ	Density
r	"Real" scenario
R	Resource
Res	Residues
$Res_{biogasslurry,overflow}$	Biogas slurry automatically streaming out of the fermenter by gravity through so-called "overflow"

$Res_{biogasslurry,recycled}$	Biogas slurry removed from the outlet and refilled into the inlet of the digester
$Res_{biogasslurry,removed}$	Biogas slurry removed from the digester and used as fertilizer
RTKC	Regional cookstoves Testing and Knowledge Centre
RU	Relative uncertainty
S	Sulphur
SGP	Specific gas production
STAN	*SubSTance flow Analysis (software)*
SUM	Total number of WBT-phases (i.e. HP_cold, HP_hot, and LP) to simulated the daily cooking task
TC	Transfer coefficients
TDBP	Tanzania Domestic Biogas Programme
TLUD	Top-Lit UpDraft
TNMHC	Total non-methane hydrocarbons
ttb	Corrected time-to-boil
TU	Technische Universität
TZ	Tanzania
TZS	Tanzanian shilling
VS	Volatile substances
WBT	Water boiling test
$\bar{x}$	Mean value
Δx	Standard error

Abbreviations of the energy alternatives (used only in Figures and Tables):

3SF	Three-stone-fire
BGB	Biogas burner
BGD	Biogas digester
CB	Charcoal burner
CP	Charcoal production
RS	Rocket stove
SG	Sawdust gasifier

A2: Appendix B to P3 - Modelling the micro sanitation system

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APPENDIX B OF

Linking Energy-Sanitation-Agriculture: Intersectional Resource Management in Smallholder Households in Tanzania

MODELLING THE MICRO SANITATION SYSTEM (MSS)

A. Krause, V. S. Rotter

Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

TABLE OF CONTENT

PRELIMINARY REMARK

Chapter B.1 describes the basic definitions of the micro sanitation system (MSS) model and introduces the alternatives that we analysed (Section B.1.1). The Chapter B.1 further includes the specific terminology (Section B.1.3), the assumptions we made (Section B.1.5) and the underlying processes we considered in the material flow analysis (MFA) (Section B.1.6. and B.1.7.). We also present the MFA-models of the four alternatives, as set up and visualized with the MFA-software we used, including an introduction of the analysed technologies.

Chapter B.2 describes the equations we used to systematically quantify relevant material flows in the MSS.

Chapter B.3 lists the plausibility criteria used in the MSS analysis. We further discuss some results of the data evaluation in addition to those discussed in the main manuscript including (i) differences in the provision of residues from the sanitation oven, (ii) variances in the carbon (C) content of toilet sludge, and (iii) present uncertainties of specific material flows in the MSS-model after computing.

In Chapter B.4, we provide (i) information on the means of the data collection and various sources from scientific theory and applied practice and (ii) a list of all parameter values that we used in Table B.8.

Finally, Chapter B.5 summarizes all flows and processes that we considered in the MSS-model, for the four alternatives in Table B.9, and shows the visualised results as flow diagrams.

All references that we used in the MSS-model are listed in Chapter B.6.

In addition, we attached pdf-documents of the spreadsheets with model calculations for the four alternatives.

B.1. General information

B.1.1. Definition of the system

The basic definition for all alternatives in the MSS includes (i) the "housing system", which represents the system's boundaries and describes the farming household, and (ii) the "attitude", which reflects the toilet use at home. The latter was introduced since, in the daytime, people often use a bathroom in places other than home, e.g. at school, in the office, at the market, etc. (Table B.1).

Table B.1: Basic description of the MSS for all alternatives (S1 to S4).

Housing system		Attitude towards using the toilet at home
Number of people per family:	6	65 % for urination
Temporal boundary in days:	365	70 % for defecation
MF [days hh^{-1} yr^{-1}]	2190	

The model factor (MF) is the product of the number of people per household and the days per year. We applied it in most equations to extrapolate material flows from a daily and personal basis ($\dot{M}$ in g p^{-1} d^{-1}) to annual flows in the farming household ($\dot{m}$ in kg hh^{-1} yr^{-1}) (Eq. B.1). For the specific flows of urine (U) and faeces (F), we also considered the attitude (Att) towards using the toilet for urination (Att_U) and defecation (Att_F) (Eq. B.2 and B.3).

$$\dot{m} = (\dot{M} \cdot MF)/1000 \quad \text{Eq. (B.1)}$$

$$\dot{m} = (\dot{M} \cdot MF \cdot Att_U)/1000 \quad \text{Eq. (B.2)}$$

$$\dot{m} = (\dot{M} \cdot MF \cdot Att_F)/1000 \quad \text{Eq. (B.3)}$$

In the MSS-model, we compared four alternatives that represent the locally available sanitation technologies (Table B.2; also see Table 3 of the main text): the current state of using pit latrines (S1), two approaches of ecological sanitation (EcoSan) with one employing a urine-diverting dry toilet (UDDT) (S2) and the other using a UDDT with additional thermal sanitation in a loam oven (S3), and a water-based sanitation system comprising a water toilet and a septic tank (S4). Sections B.1.4-B.1.7 further introduce these technologies.

Table B.2: Pictures, description of construction and operation, and local prices of technologies analysed in the MSS-model for farming households in Karagwe, Tanzania.

S1	S2	S3	S4
PL Pit Latrine	EcoSan UDDT only	CaSa UDDT and sanitation oven	WC + ST Water toilet (Closet) and Septic Tank
			
The substructure of the latrine toilet can be built from locally available material. Part of the grey water is disposed into the toilet, too. Often, ashes are added to the pit to avoid bad odours.	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 smelling. 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.		Toilets are available for sitting or squatting. Flush water is used to transport toilet waste from WC into ST. Parts of the grey water are disposed into the system, too.
The pit latrine is an accumulation system, i.e. material is constantly covered by new material. The pit is usually unlined so that the liquid phase soaks away and effluent infiltrates the surrounding soil. The solid phase remains in the pit and is slowly decomposed in predominantly anaerobic conditions.	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 rotation basis into a planting hole for a tree or cutting of a banana plant. This practice is locally called *omushote*.	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].	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.
Made of mud/grasses, roofed with iron sheets: ≈ 250,000 TZS ≈ 100 € (labour costs). Made of bricks with roofing tiles: ≈ 900,000 TZS ≈ 360 € (material & labour costs)	≈ 450,000 TZS ≈ 180 € (material costs) ≈ 500,000 TZS ≈ 200 € (labour costs)	≈ 630,000 TZS ≈ 250 € (material costs) ≈ 500,000 TZS ≈ 200 € (labour costs)	1,600,000-2,000,000 TZS ≈ 640-800 € (material and labour costs)

Non-common abbreviations: CaSa-project "Carbonization and Sanitation"; EcoSan: ecological sanitation; UDDT: urine-diverting dry toilet; TZS: Tanzanian shilling.
Notes: Costs were transferred from TZS to € by applying an exchange rate of 1,000 TZS = ≈0.40 €.
Sources for the costs: Expert judgement (Mavuno, 2015) for S1 and S4; CaSa project-accounting, pilot phase 2012 for S2 and S3.
S1: photo: A. Krause; drawing: Brikké and Bredero, 2003; S2: photo: A. Krause; drawing: http://www.ingenieure-ohne-grenzen.org/de/content/download/23394/134705/file/How%20to%20build%20a%20UDDT%20–%20Construction%20Manual%20–%20English.pdf; S3: photo: A. Krause; drawing: http://www.ingenieure-ohne-grenzen.org/de/content/download/23393/134699/file/How%20to%20build%20an%20oven%20–%20Construction%20Manual%20–%20english.pdf; S4: photo: A. Bitakwate; drawing: http://www.unep.or.jp/ietc/Publications/TechPublications/TechPub-15/2-4/4-1-3.asp; last access: 21 Feb, 2016.

[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.

B.1.2. Basic information on the computational work

We performed the MFA by combining computational work in Excel with the MFA-software STAN[3]. First, we combined data collection, data evaluation, and calculations for all alternatives in one **Excel** file comprising various **spreadsheets**:

- Calculation of the nutrient content in human excreta (Section B.2.1. I);
- Summary of data on various process and material values, which comprises data from literature, calculations based on literature values, and assumptions based on literature and/or expert judgment (see Table B.9);
- Summary of auxiliary calculations to determine relevant values for modelling including data from literature or from our own experiments in Karagwe, Tanzania (TZ), in March, 2015 (e.g. water content in toilet sludge, density of dry material used as toilet additive in a UDDT, moisture in solids leaving the UDDT, etc.;
- Calculations of material flows of each alternative S1 to S4 in one sheet, structured in three parts:
  1. “Auxiliary values” provide molar weights, elemental mass percentages, global warming potentials (GWP), and eutrophication potentials (EP) for selected chemical substances;
  2. “Material and process values” comprise selected values from data collection that were required for the calculations in this sheet (e.g. loads/concentrations for faeces and urine, specific emissions, transfer coefficients, etc.);
  3. “Flows for STAN” show calculations of material flows ($\dot{m}$) on the layer of goods (G) and indicator substances C, nitrogen (N), and phosphorus (P).
- Summary of selected plausibility criteria for crosschecking the estimated values from our model with reliable data from literature sources (Table B.7);
- Spreadsheet summarizing all calculated flows from the four alternatives to be transferred to STAN, which was done via copy/paste from Excel to the “data transfer Table” in STAN;
- Summary of results with values for $\dot{m}_{input}$, $\dot{m}_{output}$, and $\dot{m}_{storage}$ derived from calculations in Excel and after data reconciliation in STAN;
- Bar diagrams presenting the results with values after data processing in STAN.

In addition, results were visualized as flow diagrams in STAN (see Supplements.).

B.1.3. Specific wording

Faeces	solid part of human excreta;
Urine	liquid part of human excreta;
Human excreta	urine and faeces;
Cleansing water	wastewater from anal cleansing after defecation;
Dry material	used in the UDDT; added after defecation, comprises a mixture of locally available dry materials, e.g. sawdust, soil, char particles, and ashes;
Solids	faeces, dry material, and some urine, which enters into the compartment for solids’ collection of the UDDT due to incomplete urine diversion;
Grey water	domestic wastewater including wastewater from bathing, cooking, washing dishes, washing clothes, and hand washing after visiting the toilet;
Flush water	water used to flush down faeces (or other solid wastes) in the water toilet.

[3] *subSTance flow ANalysis* (STAN) is a freeware developed by the Institute for Water Quality, Resources and Waste Management at Vienna University of Technology (Cencic and Rechberger, 2008; Cencic et al., 2012).

B.1.4. General description of the analysed sanitation systems including flow diagrams

Before going into more detail, we will shortly introduce the case study of this work and provide an overview of the selected sanitation technologies that we analysed in the alternatives S1 to S4 (Table B.1) as well as the respective treatment processes (Table B.2). We further present the individual models as set up in the MFA-software. There, all $\dot{m}$ are depicted as black arrows, processes as black boxes, and processes that contain further sub-processes as blue boxes.

We selected the alternatives based on **local conditions**, which were assessed according to the national census of agriculture in the Kagera region (Tanzania, 2012): Currently, ≈ 88 % of the households in Karagwe district use traditional pit latrines as sanitation facilities and ≈ 4 % use ventilated, improved pit latrines. Another ≈ 1 % use a system of flush or pour water toilets in combination with septic tanks, and ≈ 6 % have no toilet; the remaining ≈1 % is of unspecified "other type".

Furthermore, recent initiatives have supported the implementation of EcoSan technologies. The **project Carbonization and Sanitation** (CaSa) deals with EcoSan including UDDT, thermal sanitation of faeces and composting of excreta mixed with biochar. MAVUNO Project (*mavuno,* Swahili for "harvest"), a local non-governmental organisation of organic farmers, facilitates the CaSa-project. After having completed the pilot study (conducted from 2012–2014), the technologies are currently implemented and tested on an institutional level (construction in 2015; operation started in the beginning of 2016) in a girls' secondary boarding school. Subsequent implementation on a household level will be planned with the community. Cooperation partners are the Technische Universität (TU) Berlin, Germany, and, formerly, the association Engineers Without Borders from Berlin, Germany. The CaSa-project is a case study for this analysis and (i) defines the approaches analysed in alternatives S2 and S3 and (ii) provides data that was collected during the pilot operation.

Table B.3 summarizes the alternatives that we analysed in the MSS-model. In general, all analysed sanitation options are classified as decentralised treatment systems. Furthermore, alternatives S1 and S4 are classified as conventional systems, in which material flows are mainly stored in the pit or tank (i.e. "one-way" systems), except for gaseous and liquid emissions to the ecosystem. Alternatives S2 and S3 are ecological systems, which aim at (i) using human excreta in the agroecosystem (AES), (ii) reducing emissions to the ecosystem, and (iii) avoiding the use of flush water (i.e. "recycle-driven" systems).

Table B.3: Overview of the system classification and treatment processes for the alternatives S1 to S4.

Alternative	S1	S2	S3	S4
Technical system classification	Waterless[4], mixed treatment[5]	Waterless treatment with source separation	Waterless treatment with source separation	Water-based, mixed treatment
Urine	Deposited in the pit	Collected and stored; can be used as mineral fertilizer	Collected and stored; can be used as mineral fertilizer	Deposited in the pit
Faeces	Deposited in the pit	Collected and stored; can be used for composting, preferably not used for food crops but for trees	Collected and thermally sanitised; used for CaSa-composting with subsequent field application; possible to also use as organic input to food crops	Deposited in the pit
Cleansing water	Deposited in the pit	Directed to a soil filter	Directed to a soil filter	Deposited in the pit
Domestic grey water	Partly deposited in the pit	Not considered in the analysis	Not considered in the analysis	Partly deposited in the pit
Flush water	Non-existing	Non-existing	Non-existing	Deposited in the pit

[4] "Waterless", i.e. without flush water.
[5] "Mixed", i.e. without source-separation, which means that urine, faeces, and wastewater are collected together.

Alternative S1 represents the current sanitation situation of most people in Karagwe and consists of a latrine toilet and an earth pit to deposit the toilet sludge.

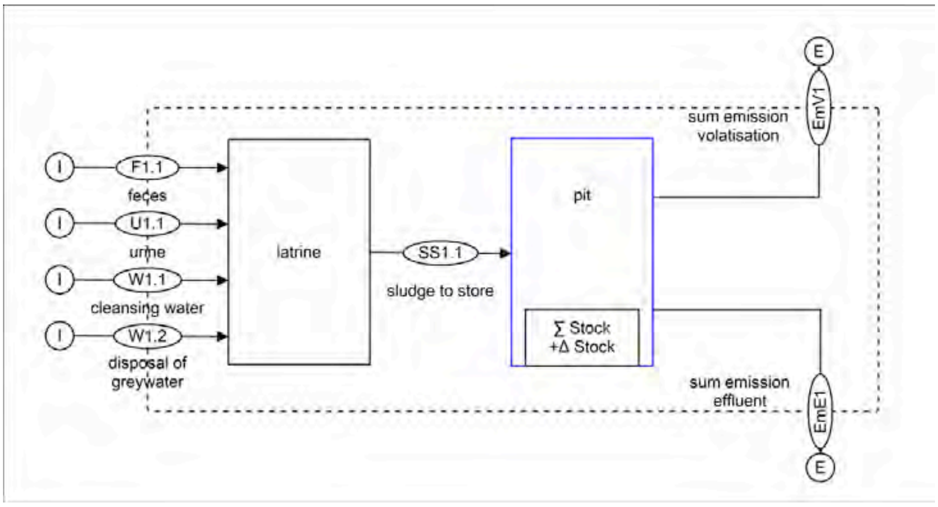

Fig. B.1: STAN-model of the alternative S1 with import (I) and export (E) flows and two main processes.
The process "pit" (in blue) contains further sub-processes (see Fig. B.5).

Alternative S2 represents the first option of a possible change of the sanitation technology, namely towards an implementation of EcoSan *without* additional thermal sanitation of the solid matter. This alternative consists of a UDDT including the separation of urine and faeces, the collection of solids, and the storage of urine.

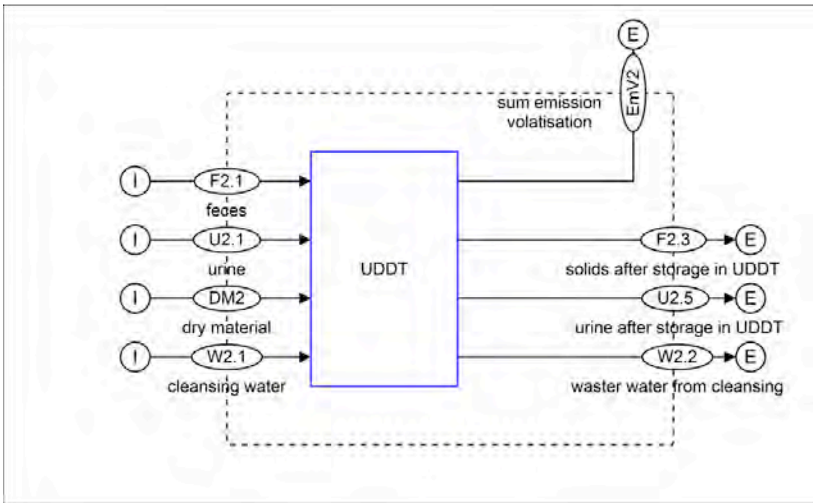

Fig. B.2: STAN-model of the alternative S2 with import (I) and export (E) flows and two main processes.
The process "UDDT" (in blue) contains further sub-processes (see Figs. B.7-B.9).

Alternative S3 represents another option of a possible change of the sanitation technology, namely towards an implementation of EcoSan *with* additional thermal sanitation of the solid matter. This alternative consists of a UDDT including the above-mentioned components and a sanitation oven where the sanitation of solids is realized via pasteurization. For this, a so-called "microgasifier" stove is used to provide the heat for the thermal treatment to the oven.

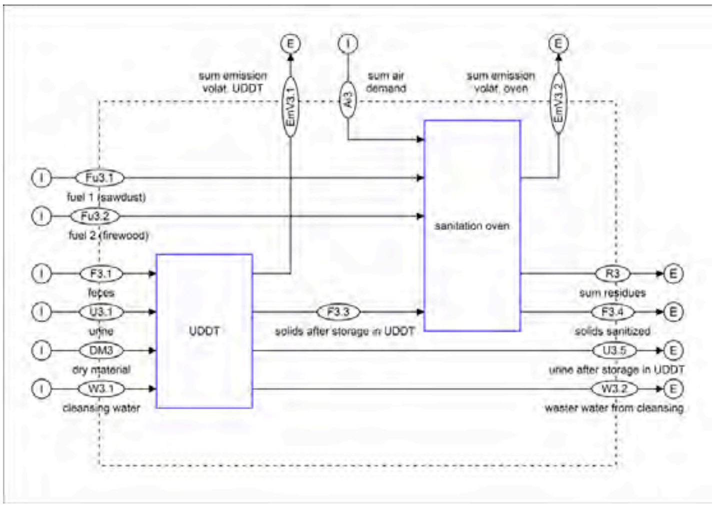

Fig. B.3: STAN-model of the alternative S3 with import (I) and export (E) flows and two main processes.
The processes "UDDT" and "sanitation oven" (in blue) contain further sub-processes
(see Figs. B.7-B.9 for the UDDT and Fig. B.10-B.11 for the sanitation oven).

Alternative S4 represents the last analysed possible change of the sanitation technology, namely towards a conventional, water-based system including a flush toilet and a septic tank.

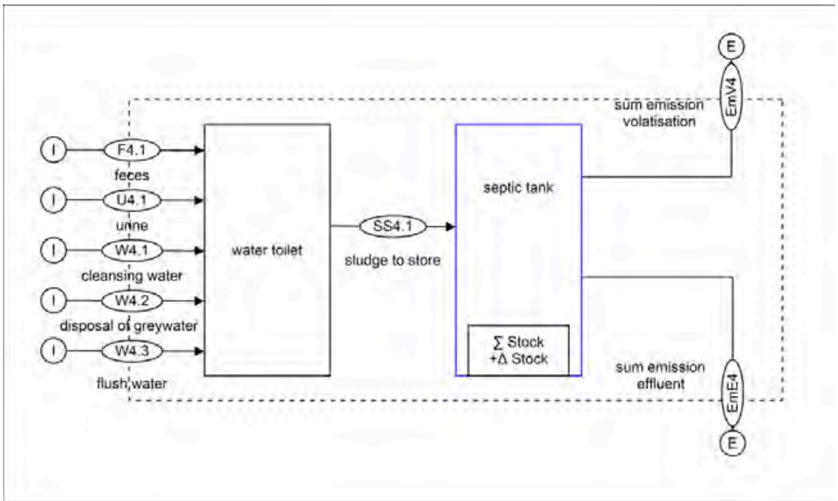

Fig. B.4: STAN-model of the alternative S4 with import (I) and export (E) flows and two main processes.
The process "septic tank" (in blue) contains further sub-processes (see Fig. B.6).

B.1.5. Basic assumptions in the MSS

Some basic assumptions that we made for modelling the MSS across the four alternatives include:

- In general, we did not consider domestic wastewater management in our system analysis; however, we included certain grey water flows in the model if they were necessary for computing other flows relevant in our research (Section B.1.6.).
- Water that is used in households (e.g. for flushing), stems from rainwater harvesting; we did not consider C and nutrient contents, in order to simplify and because of data gaps regarding site-specific nutrient concentrations in rainwater.
- Due to water scarcity in Karagwe, cleansing water is not used after urination, only after defecation.
- The predominant process in the toilet or pit in S1 and S4 is the biochemical degradation of organic matter (OM), which is partly anaerobic and partly aerobic (Doorn et al., 2006; Reid et al., 2014a).

- Neither gas nor sludge from the pit latrine (S1) or the septic tank (S4) was further utilised; gas was emitted to the atmosphere and sludge remained in the pit as stock after gaseous and liquid emissions.
- The main metabolic process in the UDDT is biochemical degradation, which is mainly aerobic and comparable to processes occurring with faeces after open defecation (Winrock, 2008).
- We did not consider degrading processes for the dry material toilet additives used in the UDDT in S2 and S3 because i) the material is very dry, which hinders degradation and ii) it shows high contents of minerals (i.e. ash and local soil) and slow-degrading lignin (i.e. sawdust).
- The sanitation process in S3 happens via pasteurisation in a loam oven heated by a microgasifier cooking stove (Figs. B.10 and 11). The used stove is comparable to the microgasifier using sawdust that was analysed in alternative E4 in the MES-model.
- All gaseous emissions to the atmosphere were quantified (Section B.2.3.) and the climate relevant ones were assessed using GWP-factors from the guidelines of the Intergovernmental Panel on Climate Change (IPCC) (Section B.3.).
- Data processing: if no standard deviation or standard error was available for collected data sets, we set the uncertainty to 30 % of the mean value.

B.1.6. Specific description of the conventional systems analysed in alternatives S1 and S4

We partly included domestic wastewater management in the analyses of S1 and S4 because a certain share of grey water from bathing, cleaning dishes and washing clothes is commonly disposed to the pit. The **grey water disposal** in these conventional sanitation systems was quantified by expert judgment (Mavuno, 2015; results in Table B.9). This liquid load was relevant in our analysis to quantify the effluent from the pit based on the final water content in sludge (Section B.2.3. II). In addition, **cleansing water** was also disposed to the toilet in S1 and S4 and **flush water** use was considered in S4 (Section B.2.1. II).

Potentially, **toilet sludge** can be recovered from the pit in S1 or S4. However, it is hazardous to human health to remove sludge from the toilet pit with buckets and add it to the field without further treatment since pathogens can easily survive in the given conditions with high contents of water, OM, and nutrients, (e.g. Bakare et al., 2012; Cheruiyot and Muhandiki, 2014; Dzwairo et al., 2006; Graham and Polizzotto, 2013; Nyenje et al., 2010). In local practice, smallholders prepare a new hole if the old one is full (Mavuno, 2015). Therefore, we assumed sludge to be stored as stock in the pit and did not consider the matter as a potential residue or recycling flow.

To take **emissions to the ecosystem** into account, we calculated (i) gaseous emissions from volatilisation and biochemical degradation (EmV; Section B.2.3.) and (ii) liquid emissions from effluents (EmE; Section B.2.3. II).

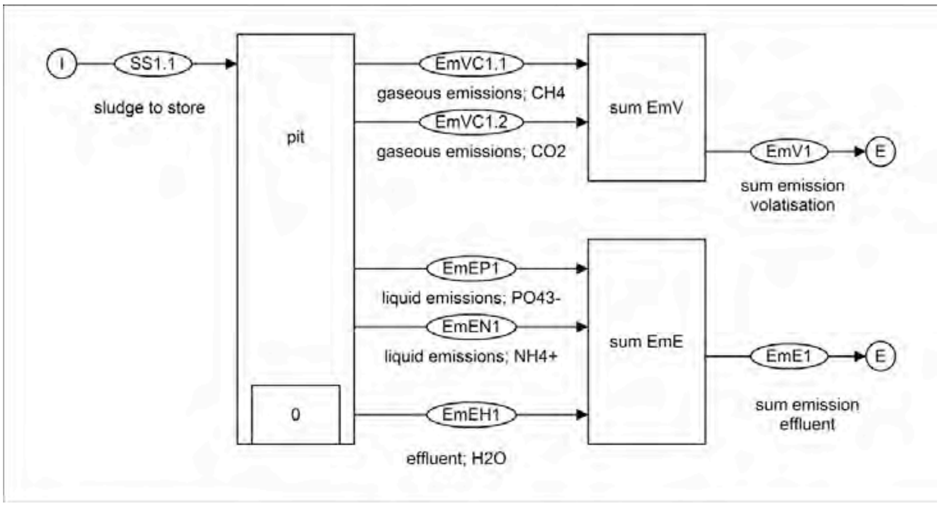

Fig. B.5: STAN-model of the process "pit" analysed in the alternative S1 and modelled with further sub-processes "sum EmE", representing the total liquid emissions from effluent, and "sum EmV", representing the total gaseous emissions from volatilisation.

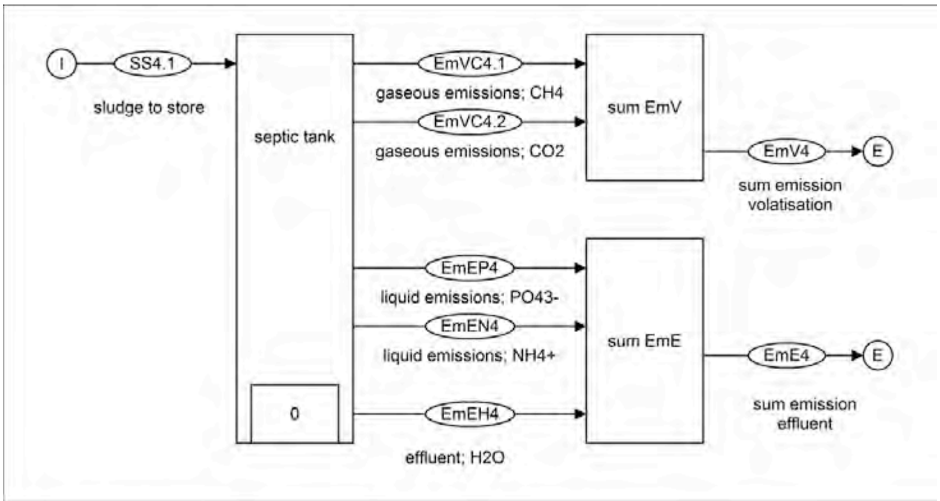

Fig. B.6: STAN-model of the process "septic tank" analysed in the alternative S4 and modelled with further sub-processes "sum EmE", representing the total liquid emissions from effluent, and "sum EmV", representing the total gaseous emissions from volatilisation.

B.1.7. Specific description of the EcoSan-systems analysed in alternatives S2 and S3

We did not consider domestic wastewater management in the EcoSan-alternatives; only wastewater used for anal cleansing in the UDDT was part of S2 and S3. In our model, we assumed that **cleansing water** is directed to a soil filter, where it is used for growing horticultural plants in the surroundings of the toilet.

Thus, the wastewater is used as a resource for irrigating flowers and bushes. This avoids bad odours, breeding sites for mosquitos in stagnant water, and contamination of groundwater through leaching (Mucunguzi, 2010; Winblad and Simpson-Hébert, 2004).

Usually, EcoSan-technologies are so-called "dry" or "waterless systems", hence there was **no flush water** used in S2 or S3.

For considering **emissions to the ecosystem**, we calculated EmV from various processes within the systems (see below). Liquid emissions *per-se* did not occur in the EcoSan-alternatives.

The two main **processes in the UDDT** comprised the "toilet" and the "collection and storage" of urine and solids (Figs. B.7-B.9) [Please note that the UDDT-model including all flows, processes and sub-processes was comparable in S2 and S3 and, thus, is presented exemplarily only for S2; the model of S3 was set up accordingly]. Below are further comments and explanations on the usage of a UDDT and the ways of treating and using faeces and urine. In sum, the UDDT-model comprised the following technical elements:

- **Toilet**: contains a urine division for transferring urine to the urine storage facility and solids to the solids' collection. However, in practice, urine division is not absolute and some urine might enter the compartment for solids; therefore, we used the urine collection rate (UCR) to describe the percentage of urine being transferred to urine storage (Eq. B.15 and B.16).
- **Urine collection**: transfers urine via pipes or tubes to the urine storage; during this process, the initial gaseous emissions occur (Eq. B.34-B.36).
- **Urine storage**: commonly, urine is stored in a closed container, e.g. a jerry can that is closed with a lid, a small tank, etc.
- **Collection and storage of solids**:
    - In alternative S2, we assumed that solids are collected and stored in a chamber as part of the UDDT.
    - In S3, we assumed that solids are collected in pots for the consecutive solid thermal treatment.
- **Filter**: cleansing water passes through the toilet to a soil filter, i.e. a flowerbed.

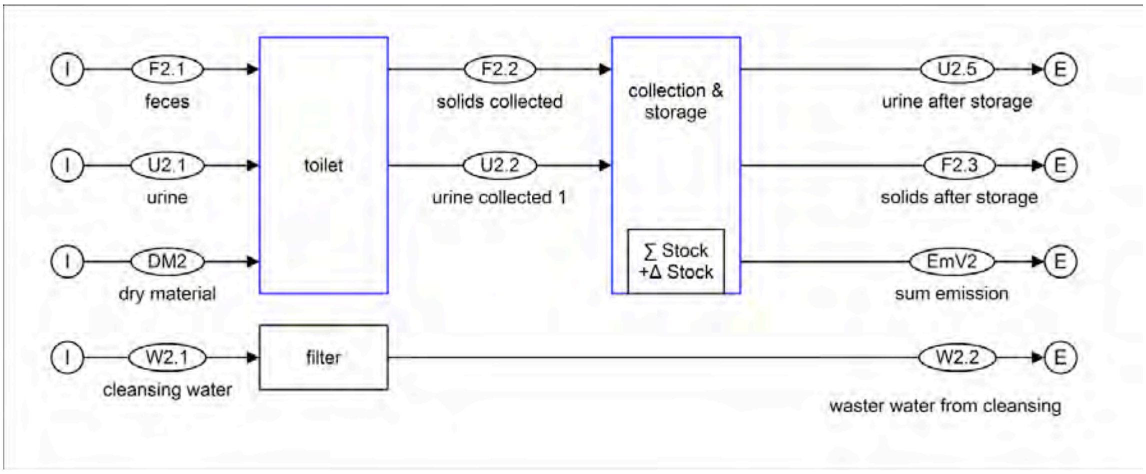

Fig. B.7: STAN-model of the of the process "UDDT" analysed alternatives S2 and S3 with import (I) and export (E) flows and two main sub-processes (in blue) containing further sub-processes (see Figs. B.8 and B.9).

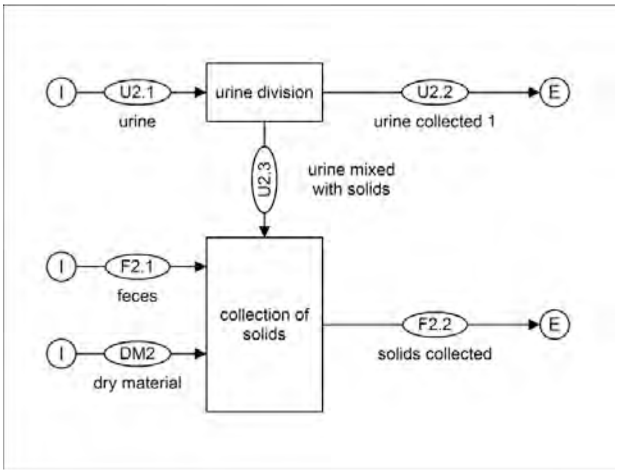

Fig. B.8: STAN-model of the sub-process "toilet" analysed alternatives S2 and S3 with import (I) and export (E) flows.

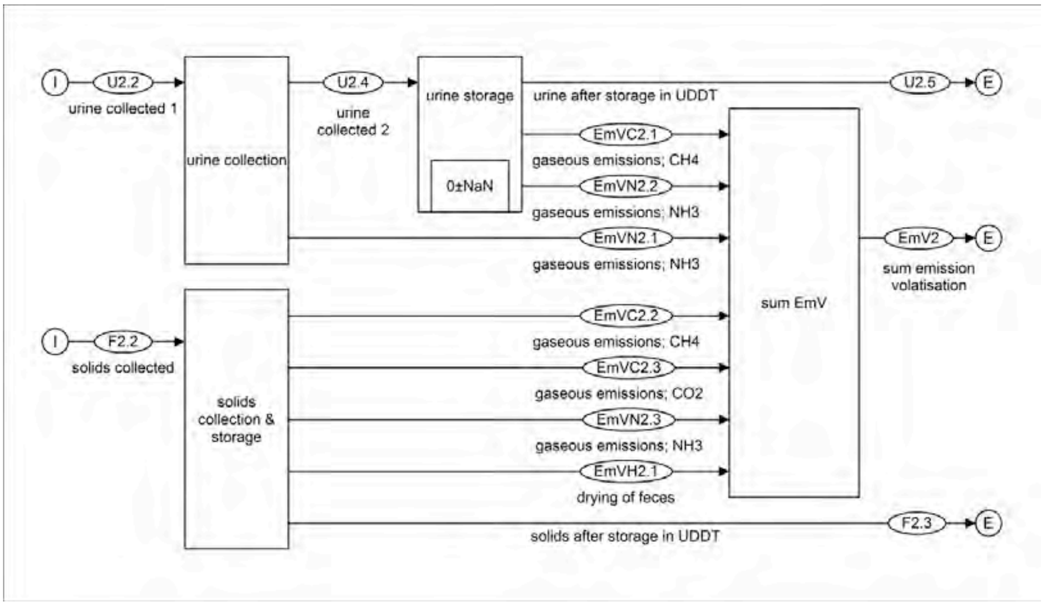

Fig. B.9: STAN-model of the sub-process "collection and storage" analysed alternatives S2 and S3 with import (I) and export (E) flows and modelled with a further sub-process "sum EmV", representing the total gaseous emissions from volatilisation.

I. Storage and use of urine

To inactivate pathogens that might be present in urine (e.g. schistosomiasis/bilharzia, hepatitis, etc.), the World Health Organization (WHO, 2006) recommends storing urine for (i) one month, if the urine is clean, or (ii) six months, if the urine if cross-contaminated with faecal particles. Niwagaba (2009) showed that if urine is not diluted, a storage period of two months at a temperature of 20° C is sufficient to allow unrestricted use of urine in agriculture.

The size of the **storage capacity** generally depends on (i) the number of people regularly using the toilet, (ii) the available resources (e.g. available material, financial resources, etc.), and (iii) the chosen storage time (see above). In accordance with the practice applied in the case study, we assumed that urine is first collected in jerry cans with a total volume of ≈ 30 dm^3 that are placed in the UDDT under the toilet slap. Afterwards, bigger containers (i.e. plastic tanks) with a volume of ≈ 200 dm^3, closed with a lid, are used for storage.

Using closed containers prevents high N-losses through ammonia emissions during storage (Richert et al., 2010). We estimated gaseous emissions based on data from literature review (Section B.2.3.III). However, we did not consider the time of storage further because - to the best of our knowledge - there is no data available on the variation of emissions over time, neither for a UDDT in general nor for urine storage in particular.

Stored urine can be used as a **mineral liquid fertilizer**, in particular as a fast acting and rapidly available N-fertilizer (Richert et al., 2010). However, it should be complemented with either mineral P and K fertilizer addition or organic amendments like compost. If used as mineral fertilizer, urine is often diluted with water, e.g. in a ratio of 1:3 up to 1:5 (*ibid.*). The main purpose is to avoid overuse of urine and to reduce the odour. If clean urine is used, Richert et al. (2010) recommend placing the urine into a furrow or hole and closing the furrow/hole with soil. This can reduce N-losses through subsurface volatilisation (*ibid*). We analysed the use of urine as fertilizer in the AES (e.g. see Appendix C).

II. Collection and use of solids in alternative S2

We assumed that in S2, solids were collected and stored inside the UDDT in a chamber underneath the toilet slap. If the chamber is full, there are two options (cf. Morgan, 2007):

1) If the UDDT has two chambers, the full first chamber is closed and a second chamber will be used. The matter remains inside the first chamber until the second chamber is full. Then, the first chamber is emptied, so that the second chamber can be closed and the first chamber will be used again. The matter from the first chamber is brought to a separate composting place or added to planting holes for trees (see below).
2) If the UDDT is constructed with one chamber only, the chamber is emptied as soon as it is full and the matter is brought to a place where composting can continue in the same way as in the first option.

For both options, the **duration** of the use of a single chamber depends on (i) the size of the chamber and (ii) the number of people using it; usually, it will be 6 months (Mucunguzi, 2010). The WHO (2006) recommends to compost faecal matter, if not additionally treated, for at least one or two years, depending on the surrounding temperatures.

Subsequently**, composting** happens on a separate composting place or directly in the soil, e.g. in holes for planting banana cuttings or other trees including fruit and timber trees. Using human excreta for cultivating bananas was a common practice in Karagwe before pit latrines were implemented in the 1940s, which is called "***omushote***" in Swahili (Rugalema et al., 1994). For either way of composting, human excreta should be mixed with other kinds of organic residues, including kitchen waste, harvest residues and also biochar or ashes. If properly done, this yields a well-balanced mixture out of C- and nutrient-rich material, fractions of easily degradable organics and of stable matter, which is suitable for humification (e.g. lignin), as well as dry and wet matter, which will sustain a well-functioning composting process (e.g. Amlinger et al., 2008; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Niwagaba, 2009).

III. Collection, treatment, and use of solids in alternative S3

We assumed that solids in S3 were additionally **thermally sanitised via pasteurisation** in a loam oven (Fig. B.10) by means of a sawdust gasifier stove (Fig. B.11), according to the CaSa-approach (Krause et al., 2015). Pasteurisation is an established sanitation process in which materials that may contain pathogens are heated up to a temperature between 60° and 95° C. This temperature is sustained for a few seconds up to one hour, according to the principle: the higher the temperature, the shorter the duration of the treatment (cf. Feachem et al., 1983; RKI, 2013; Schönning and Stenström, 2004).

On the one hand, thermal treatment of solid waste requires resources and causes emissions, on the other hand, the composting period is shortened to three to six months as pathogens are already inactivated. An additional advantage of this method is that time and temperature can be monitored throughout the sanitation process, which ensures complete pasteurisation and inactivation of pathogens. Overall, pasteurisation is a relatively safe treatment. We further argue that pasteurisation is an appropriate **technical barrier** to avoid disease transmission at a very early stage due to the fast destruction of pathogens (Schönning and Stenström, 2004). Thus, disease transmission through flies and fluids is already avoided during (aboveground) composting.

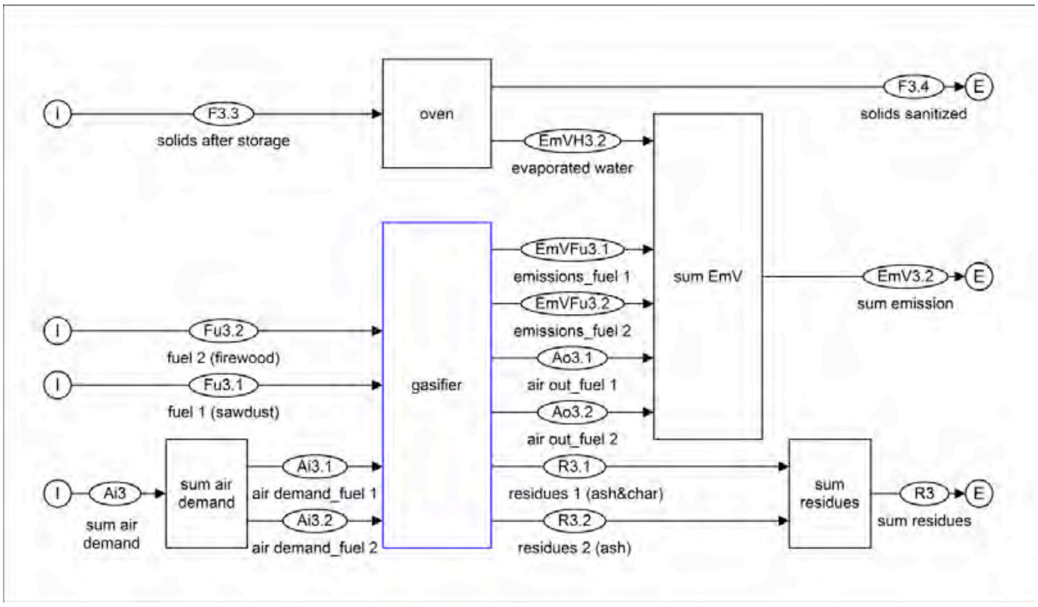

Fig. B.10: STAN-model of the sub-process "sanitation oven" analysed alternative S3 with import (I) and export (E) flows and modelled with further sub-processes "oven", "gasifier" (see Fig. B.11), and "sum EmV", summarizing the total gaseous emissions.

Inside the stove, gasification thermo-chemically decomposes sawdust into (i) wood gas and (ii) ash and char (Fig. B.11). Subsequently, the wood gas is completely oxidised in the combustion chamber at the top of the stove. During operation, one frequently adds pieces of firewood (so-called "firing sticks") to enhance the firepower of the microgasifier stove and to accelerate the heating process in the oven. This is necessary because, due to its size, heating the loam oven requires a higher energy input than cooking on the stove. To simplify, we assumed that the additional firewood is completely oxidised, i.e. directly combusted without intermediate gasification processes. After the sanitation operation, ash and char remain as residues and were accounted for as a potential recycling flow to the AES.

In the MSS-model, composting of stored (S2) or sanitised (S3) solids from UDDT was *not* part of the analysis. The use of sanitised solids from S3 was integrated in another model analysing the AES through CaSa-composting and amendment of CaSa-compost as an organic input (Krause and Rotter 2017).

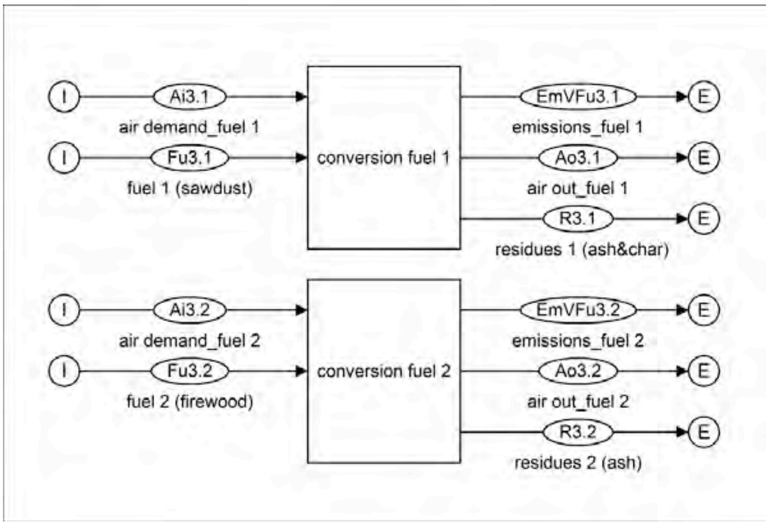

Fig. B.11: STAN-model of the sub-process "gasifier" analysed alternative S3 with import (I) and export (E) flows and modelled with a further sub-process for the thermo-chemical conversion of fuel 1 and fuel 2.

In the MSS-model, we only considered storage of solids in the UDDT, whereby the initial processes of biochemical degradation occur (Section B.2.3. III). As with urine storage, we did not further consider variances in the time period for storing solids inside the toilet, due to the lack of scientific work quantifying emissions from UDDT over time. But, as mentioned above, the retention time of solids in the UDDT is probably several weeks to months in S2 and merely several days to one or two weeks in S3. Therefore, assuming equal emissions from S2 and S3 is a simplification that may overestimate emissions from S3, but it was necessary due to the data gaps.

B.2. SPECIFIC SET OF EQUATIONS

In this chapter, we explain the set of equations that we applied for analysing the MSS in addition to the main equation representing the "principle of mass conservation" (Eq. 1 of the main text). We first carried out all mathematical operations with the arithmetic mean value ($\bar{x}$). Then, we calculated the standard error (Δx), which derives from the standard deviation (σ) of the test series or collected data set as well as the relative uncertainty (RU), which is defined as Δx in % of $\bar{x}$ (Brunner and Rechberger, 2004). This corresponds to *Gauss's law of error propagation* (Brunner and Rechberger, 2004; FAU physics, n. d.), which differs for addition or subtraction (Eq. B.4 and B.5) and multiplication or division (Eq. B.6 and B.7).

If $y = c_1\bar{x}_1 + c_2\bar{x}_2 + \ldots + c_k\bar{x}_k$ with $c > 0$ (addition) and $c < 0$(subtraction) then:

$\Delta y = \sqrt{(c_1\Delta x_1)^2 + (c_2\Delta x_2)^2 + \ldots + (c_k\Delta x_k)^2}$ Eq. (B.4)

and $RU_y = \Delta y/\bar{y}$ Eq. (B.5)

If $y = c\bar{x}_1^{m_1} \cdot \bar{x}_2^{m_2} \cdot \ldots \cdot \bar{x}_k^{m_k}$ with $m > 0$ (multiplication) and $m < 0$ (division) then:

$RU_y = \sqrt{(m_1 RU_1)^2 + (m_2 RU_2)^2 + \ldots + (m_k RU_k)^2}$ Eq. (B.6)

and $\Delta y = RU_y \cdot \bar{y}$ Eq. (B.7)

Annotation on the conventions that we applied for labelling the flows in the calculations:

The so-called layer of modelling is indicated with the first index after the abbreviation of the flow (e.g. F_P as flow of P in faeces). Furthermore, many flows are numbered in their order of appearance in the system, e.g. U1, U2, U3 for various urine flows in the EcoSan-alternatives. However, in the Excel as well as in the STAN-model, we adjusted these abbreviations so that the alternative number was included before the urine flow number, i.e. U1.1 is urine flow U1 in alternative 1; U2.1 is urine flow U1 in alternative 2; U2.3 is urine flow U3 in alternative 2, etc.

B.2.1. Input flows: materials collected in the sanitation systems

I. Material, C and nutrient flows of urine and faeces

From comparable studies, we collected data on total $\dot{m}_{input}$ of excreted urine and faeces in fresh matter (FM) on the layer of G and on C contained in urine and faeces (Table B.9). Values were given in quantities per person per day, which we extrapolated to annual $\dot{m}_{input}$ of **urine ($U1_G$ and $U1_C$)** and **faeces ($F1_G$ and $F1_C$)** by applying Eq. B.2 and Eq. B.3. Usually, there are high variations in the volume and mass of faeces over time (e.g. throughout a week), between individuals (e.g. children versus adults), and between different geographic regions (e.g. Europe versus Africa). The latter is mainly due to differences in the common diet (e.g. fibre- or meat-based diet). Pursuant to Londong (2015), we determined a comparatively high load of faeces per person and day as a starting point, because the daily diet in TZ commonly consists of high food consumption but lower water consumption as compared to Europe. According to local experts, it is also common in Karagwe to drink less and use food as the main source of water.

To estimate $\dot{m}_{input}$ of N and P contained in human excreta, we applied the approach of Jönsson and Vinneras (2004) for correlating the protein content in food with the nutrient content in excreta. This approach has been validated for several countries including China, Germany, South Africa, Sweden and Uganda (Jönsson and Vinneras, 2004; Meinzinger, 2010). The "national food balance sheets" by the Food and Agriculture Organization (FAO, n.d.) provided nutritional data for TZ. From data on the per capita supply of proteins through vegetal and animal products in gram per day for the years 2007–2011, we calculated the five-years-average. Then, we calculated the content of N and P in human excreta (Ex) from the equations of Jönsson and Vinneras (2004):

$$Ex_N = 0.13 \cdot Grand\ total_{Prot} \qquad \text{Eq. (B.8)}$$

$$Ex_P = 0.011 \cdot (Grand\ total_{Prot} + Vegetal\ products_{Prot}) \qquad \text{Eq. (B.9)}$$

$$Grand\ total_{Prot} = Vegetal\ products_{Prot} + Animal\ products_{Prot} \qquad \text{Eq. (B.10)}$$

With $Animalproducts_{Prot}$ as the content of proteins in animal products consumed by one person per day [g p^{-1} d^{-1}], etc.

Based on our literature review, we started from the premise that urine contains 80 % of N and 60 % of P, whilst the remaining nutrients are contained in faeces (Jönsson and Vinneras, 2004; Meinzinger, 2010; Montangero, 2006). Jönsson and Vinneras (2004) found that the more the food is processed, the easier it can be digested and the more nutrients will be found in urine. We classified the processing level of the food in Karagwe as average (e.g. cooked banana, cooked beans, cooked rice, porridge, etc.). Thus, we used means of the values for nutrients in urine and faeces for our model. Furthermore, we deduced the error for F_N and U_N as well as for F_P and U_P from comparing lower and upper values, as provided by Jönsson and Vinneras (2004) and Meinzinger (2010).

With these results, we calculated the remaining annual $\dot{m}_{input}$ of urine ($U1_N$ and $U1_P$) and faeces ($F1_N$ and $F1_P$) in the household by applying Eq. B.2 and Eq. B.3.

II. Partial wastewater management: cleansing, grey and flush water

The use of cleansing water (in g p^{-1} $defecation^{-1}$) was estimated on the basis of data from literature combined with local expert judgement (Table B.9). In addition, we assumed that each person would defecate once daily. Then, we calculated the annual $\dot{m}_{input}$ of **cleansing water** ($W1_G$) by applying Eq. B.3. Nutrient and C contents in cleansing water were not considered (Section B.1.5).

To quantify $\dot{m}_{input}$ of grey water to the pit (S1) and to the septic tank (S4), we first estimated the daily water consumption per person for bathing, cooking, washing clothes, washing dishes and hand washing based on literature and expert judgment. Then, we evaluated which flows of wastewater are commonly disposed to the toilet ($W_{disposal,i}$) and the extent of these flows ($frac_{disposal,i}$) by consulting experts. We considered the total amount of wastewater disposed to the MSS per person and day ($W_{G,disposal,total}$) to be the sum of the various fractions (Eq. B.11).

According to expert judgment, members of households possessing a pit latrine (S1) dispose wastewater from bathing and washing clothes partially into the toilet. In households with a septic system (S4), wastewater from bathing, washing closes, and washing dishes is partially disposed into this system. That might be the case because toilets are more often located inside the house if a septic system is implemented and, thus, are closer to the kitchen.

$W_{G,disposal,total} = \sum_{i=1}^{n} W_{G,disposal,i} \cdot frac_{G,disposal,i}$ Eq. (B.11)

With n = 2 in S1 and n = 3 in S4.

Then, the total annual $\dot{m}_{input}$ of **grey water disposed ($W2_G$)** was estimated using Eq. B.1. The contents of C, N, and P contained in generic domestic grey water were calculated with the respective concentrations (c) derived from literature review (Table B.9) and by applying Eq. B.12. Extrapolation to the annual flow was done with Eq. B.1.

$W2_P = (W2_G \cdot c_{W2,P})/1000$ Eq. (B.12)

Exemplary equation for P in total disposed wastewater ($W2_P$) where $c_{W2,P}$ is the concentration of P in $W2_G$ in g dm^{-3}, which was assumed to be equivalent to g kg^{-1}, if grey water has a density of 1 kg dm^{-3}.

In S4, flush water was used additionally. Literature review combined with local expert judgment suggested that each household member uses 10 dm^3 flush water per day and only after defecation. This is a water-conserving practice since water is scarce in Karagwe. The total annual $\dot{m}_{input}$ of **flush water** ($W3_G$) was estimated by applying Eq. B.3. Nutrient and C contents in flush water were not considered (Section B.1.5).

III. Sludge to store in the conventional systems analysed in S1 and S4

The total $\dot{m}_{input}$ for depositing in the pit is called **"sludge to store"** ($SS1_G$). It is the sum of all $\dot{m}_{input}$ to the toilet *before* any (gaseous and liquid) emissions occur and was calculated for S1 (Eq. B.13) and S4 (Eq. B.14).

$SS1_G = F1_G + U1_G + W1_G + W2_G$ Eq. (B.13)

$SS1_G = F1_G + U1_G + W1_G + W2_G + W3_G$ Eq. (B.14)

Both equations are exemplary for determining the sludge flows on the layer of G; flows on the layer of C, N, P were calculated accordingly.

B.2.2. Input flows: additional materials required in the ecological sanitation systems

I. UDDT specifics: addition of dry material toilet additives and urine division

In a UDDT, dry material (DMT) is added after defecation to cover the faeces and to accelerate their dehydration, which reduces bad odours and also constitutes the first sanitation step. The composition of dry material in terms of volume was estimated as follows, based on data collected from the case study: sawdust (fracV: 40 m^3 m^{-3}), soil (40 m^3 m^{-3}), and ashes (20 m^3 m^{-3}). As part of the auxiliary calculations, we determined the density of the mixture (δ in kg dm^{-3}) by using the assumed composition and collected data on the specific densities of the mixed materials:

$\delta_{DMT} = \delta_{sawdust} \cdot fracV_{sawdust} + \delta_{soil} \cdot fracV_{soil} + \delta_{ash} \cdot fracV_{ash}$ Eq. (B.15)

Then, we determined the mix in terms of masses (fracM in kg kg^{-1}):

$fracM_{sawdust} = \delta_{sawdust} \cdot frac_{sawdust} / (\delta_{sawdust} \cdot frac_{sawdust} + \delta_{soil} \cdot frac_{soil} + \delta_{ash} \cdot frac_{ash})$ Eq. (B.4)

Exemplary for determining the mass fraction of sawdust ($fracM_{sawdust}$) in the total mixture of dry material.

The elemental concentrations for C, N, P in FM of the mix of dry material (e.g. DM_C) was calculated by using the specific concentrations in the mixed materials:

$c_{C,DMT} = fracM_{sawdust} \cdot c_{C,sawdust} + fracM_{soil} \cdot c_{C,soil} + fracM_{ash} \cdot c_{C,ash}$ Eq. (B.16)

where $c_{C,DMT}$ is the concentration of C in FM of dry material, and $c_{C,sawdust}$ is the concentration of C in FM of sawdust material, etc.

Based on experiences from the case study, we assumed that each household member adds 0.2 ± 0.02 dm^3 per day to the UDDT. With δ_{DM}, we calculated the addition of dry material in kg p^{-1} d^{-1}, which was extrapolated to the total annual $\dot{m}_{input}$ of dry material in the household by applying Eq. B.3. The respective $\dot{m}_{input}$ on the layers of C, N, P were calculated by using the elemental concentrations in FM of dry material (e.g. $c_{C,DM}$; determined by applying Eq. B.17):

$$DMT_C = DMT_G \cdot c_{C,DMT} \quad \text{Eq. (B.17)}$$

Exemplary for determining the flow of C in DMT; flows of N and P related with DMT were calculated accordingly with $c_{N,DM}T$ and $c_{P,DMT}$, respectively.

As mentioned above (Section B.1.7), **urine division** is usually incomplete and some urine enters the compartment for solids. In general, successful urine division depends on (i) the motivation of the users, (ii) the information users receive about the functioning of the UDDT (particularly on urine division), and (iii) the construction design (Jönsson, 2001; Meinzinger, 2010). The UCR describes the ratio (in %) of the urine transferred to urine storage. This parameter can vary from 60 % to 90 % (Jönsson, 2001; Meinzinger, 2010; Vinneras and Jönsson, 2002).

From the total annual $\dot{m}_{input}$ of urine in the model household ($U1_G$), we deduced the "**urine collected I"** ($U2_G$; Eq. B.18) and the "**urine mixed with faeces"** ($U3_G$; Eq. B.19).

$$\text{U}2_G = U1_G \cdot UCR \quad \text{Eq. (B.18)}$$

$$\text{U}3_G = U1_G \cdot (1 - UCR) \quad \text{Eq. (B.19)}$$

Exemplary for determining the urine flows on the layer of G; $U2_N$ or $U3_N$ and $U2_P$ or $U3_P$ were calculated accordingly with $U1_N$ and $U1_P$, respectively.

Then, the total annual $\dot{m}_{input}$ of "**solids collected in the UDDT"** ($F2_G$) was calculated:

$$F2_G = F1_G + DMT_G + U3_G \quad \text{Eq. (B.20)}$$

Exemplary shown for determining the solids' flows on the layer of G; $F2_N$ and $F2_P$ were calculated accordingly with $F1_N$, DMT_N, $U3_N$ and $F1_P$, DMT_P, $U3_P$, respectively.

II. Fuel input to the sanitation oven as analysed in S3

In pasteurising the solids, we used a microgasifier to heat the sanitation oven. We determined the fuel consumption of the microgasifier during operation with an experiment conducted on-site in March 2015.

Short description of the experiment:

According to the pilot project of the case study, two kinds of fuels fired the oven: sawdust (fuel 1) and firewood (fuel 2). Before starting the operation, sawdust was packed into the microgasifier. Then, the stove was ignited with small sticks. During operation, pieces of firewood (firing sticks) were frequently added. In the experiment, we first measured the amount of the sawdust, which was used for the initial filling of the stove. Then, we continuously measured the additional fuse of firewood piece by piece. The experiment was conducted with a replication of n = 3. On average, the duration of the experiment was 250 ± 7 minutes. The low variance indicates that the three sample treatments are comparable.

When evaluating the collected data, we calculated the average quantity of fuel used per mass unit of solids in the pot *before* the treatment. We found that for pasteurisation in the sanitation oven of the CaSa-pilot project, 0.13 ± 0.02 g of sawdust and 0.17 ± 0.02 g of firewood were required (fuel requirement, FR) per gram of solids to be treated (i.e. F3). From this, we derived the $\dot{m}_{input}$ of **fuels (**$Fu1_G$ and $Fu2_G$) that is required by the sanitation processes for treating the solids occurring in the model household within one year.

$$Fu1_G = F3_G \cdot FR_{sawdust} \quad \text{Eq. (B.21)}$$

$$Fu2_G = F3_G \cdot FR_{firewood} \quad \text{Eq. (B.22)}$$

For the analysis of the MES, we derived the elemental concentrations of C, N, and P in FM of sawdust and firewood (e.g. $c_{C,fuel1}$) from literature review (Table A.12 in Appendix A). The $\dot{m}_{input}$ of C and nutrients corresponding to the fuel inputs were determined with Eq. B.18. Additionally, the combustion of fuel requires oxygen, which is provided through ambient air, i.e. imported from the atmosphere. Appendix A (Section A.2.3. III) explains the presumed stoichiometric and applied equations to estimate the oxygen demand and the corresponding $\dot{m}_{import}$ of air (i.e. Ai1 and Ai2).

B.2.3. Output flows: gaseous and liquid emissions to the ecosystem

I. Gaseous emissions from the conventional systems analysed in S1 and S4

The biochemical degradation of sludge in the pit latrine (S1) and the septic tank (S4) can include both anaerobic digestion and aerobic oxidation (Wilhelm et al., 1994). The latter is enabled by oxygen supply via gaseous diffusion through the unsaturated sediments (*ibid.*), which is likely to happen on light soils like the present Andosol. However, in an accumulative system like a pit or septic tank, we may well presume that usually the dominant anaerobic processes take place. In our model, we considered CH_4 and CO_2 as gaseous emissions from the conventional systems in S1 and S4.

We did not consider any gaseous N emissions (i.e. N_2, N_2O, NH_3) from the MSS in S1 or S4. With this, we are in line with the IPCC who stated that N_2 or N_2O emissions from denitrification are only relevant for advanced centralised treatment plants (Doorn et al., 2006). Montangero (2006) also neglected N_2O emissions and only focused on nutrient losses from leachate when analysing material flows in sanitation systems in Vietnam. In contrast, Jacks et al. (1999) estimated that N_2 emissions from pit latrines used in Botswana could account for around 30–80% of total N contained in sludge. However, in this work, products of denitrification were not measured but calculated only as a remainder of N in the mass balance and these calculations showed high uncertainty. We assume that neglecting N_2 or N_2O emissions is an appropriate simplification for our model. We argue that in Karagwe, (i) earth pits are commonly used for storing toilet sludge, which enables soil infiltration of liquid phases and counteracts denitrification; (ii) the local soil is classified as a light soil, so it is probably well drained; and (iii) the groundwater table is below the pit so that stagnant water is not likely to be present in the pit. Nevertheless, N_2O emissions are more likely to occur in septic tanks built out of concrete as the material reduces leaching and thereby promotes denitrification processes (Graham and Polizzotto, 2013).

Furthermore, we neglected ammonia volatilisation since we presumed a low ventilation rate and neutral pH in pit latrines (Graham and Polizzotto, 2013; Jacks et al., 1999; Montangero and Belevi, 2007), due to the common practice of adding ashes to the toilet pit to reduce bad odours (EfCoiTa, 2013; Mavuno, 2015).

To quantify **methane emissions** from domestic wastewater treatment or other discharge pathways, Doorn et al. (2006) introduced an emission factor (EF) in kg of CH_4 per each kg of organics present in the wastewater, which is commonly expressed in BOD (i.e. biochemical oxygen demand). The EF derives from multiplying the maximum CH_4-producing capacity (i.e. B_o in kg CH_4 kg^{-1} BOD) with a methane correction factor (MCF). The MCF indicates the degree to which a system is anaerobic. A value of MCF = 0 indicates fully aerobic conditions whilst MCF = 1 indicates fully anaerobic conditions, and MCF < 0.7 is used for analysis of systems in which the water table is below the latrine.

Subsequently, we calculated the daily CH_4 emissions per person:

$$EM_{CH4} = EF \cdot BOD = B_0 \cdot MCF \cdot BOD_{Africa} \qquad \text{Eq. (B.23)}$$

To the best of our knowledge, there is no country-specific B_o value available for TZ, so we used the default value as recommended by the IPCC, namely 0.6 kg CH_4 kg^{-1} BOD. In addition, Doorn et al. (2006) provided default values for BOD in domestic wastewater, which in African countries on average is 37 ± 0.5 g p^{-1} d^{-1}.

The MCF in a specific region or district depends on the local groundwater level (Reid et al., 2014a). Fan et al. (2013) provided groundwater models, including TZ (Fig. B.12), which show that Karagwe is predominantly characterised by a deeper water table. Usually, toilet pits in Karagwe have an average deepness of 2–5 m with a maximum of 15 m (Mavuno, 2015), whilst the ground water table in Karagwe is about -20 m.

Next, we chose a default value for MCF provided by Doorn et al. (2006) for “latrine” toilets used in “dry climate, with groundwater table lower than latrine, by small families (3–5 persons)” given with 0.1 ± 0.05. The authors also advised to integrate the “degree of utilisation of treatment or discharge pathway”, which they quantified with 0.28 for rural areas in Kenya, a neighbouring country of TZ. However, we presumed a higher value of 0.6 to integrate expert judgment and reflect the local attitude towards toilet use (Mavuno, 2015).

Reid et al. (2014a) also provided specified MCFs and EFs for various countries, including TZ, depending on local hydrology by using spatial analyses of population, urbanisation, and groundwater level. The rural EF for CH_4 emissions from pit latrines in TZ was given with 0.139 ± 0.043 kg CH_4 kg^{-1} BOD. Given the specific local conditions with a deeper groundwater table compared to other regions in TZ (Fig. B.12), the EF for Karagwe is probably lower than the national mean value (Reid et al., 2014a).

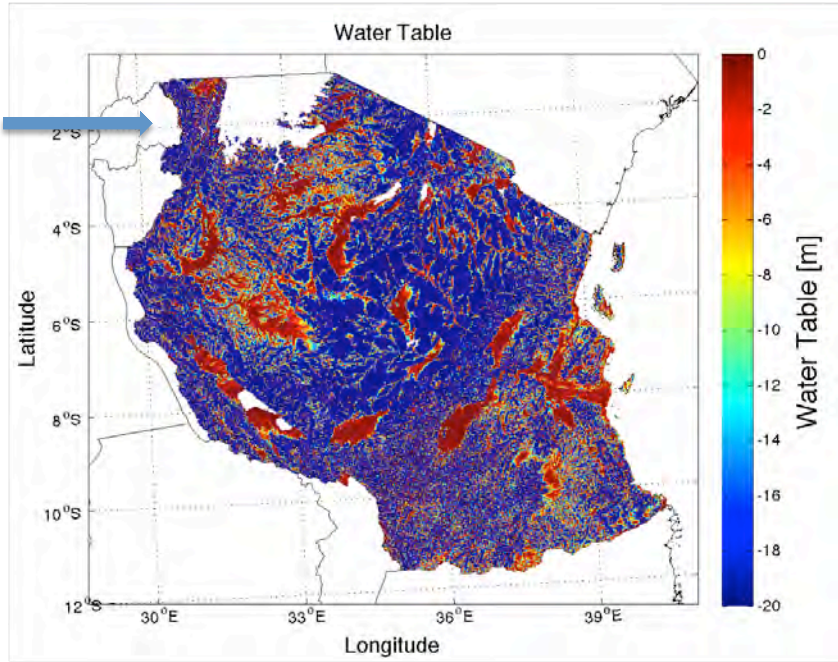

Fig. B.12: Map of TZ from the groundwater model of Fan et al. (2013);
Karagwe district is located in the northwest of TZ, indicated with the blue arrow.

Hence, we considered two cases within S1 (S1_1 and S1_2) to indicate the variance between the approaches of Doorn et al. (2006) and Reid et al. (2014a) (Table B.4). Additionally, we also considered variations in the analysis of S4 (Table B.4) since local experts revealed that septic tanks in Karagwe are constructed in different ways. The majority of households (hh) use unlined earth pits (≈ 56 % of hh operate a water-based septic system) whilst ≈ 38% of hh have a concrete tank and only ≈ 6 % of hh use a plastic tank. We performed all calculations separately for each sub-alternative. Subsequently, we estimated the results for S1 and S4 by determining the mean value from the results of the sub-alternatives.

In addition to CH_4, **CO_2 emits** from the pit/septic system (Wilhelm et al., 1994). For simplification purposes, we assumed that glucose reacts to form gaseous CH_4 and CO_2, as described in Sattler (2011) and Toprak (n.d.), to determine the corresponding flows of CO_2 (Eq. B.25).

$$C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3\ CO_2$$

Table B.4: Variations within the alternative due to variances in data sources

S1_1) CH_4 calculated acc. to Reid et al., 2014, with MCF = 0.23 and without considering U.
S1_2) CH_4 calculated acc. to Doorn et al., 2006 (IPCC), with MCF = 0.1 and U = 60%.
S4_1) CH_4 calculated acc. to Reid et al., 2014, with septic tank considered like a pit latrine with an unlined pit (equivalent to S1_1).
S4_2) CH_4 calculated acc. to Reid et al., 2014, with MCF = 0.5 for septic tank and without considering U.
S4_3) CH_4 calculated acc. to Doorn et al., 2006 (IPCC), with MCF = 0.1 for pit latrine and U = 60%.
S4_4) CH_4 calculated acc. to Doorn et al., 2006 (IPCC), with MCF = 0.5 for septic tank and U = 60%.
S4_5) CH_4 calculated acc. to field-measurements of Winrock, 2008, with septic tank considered to be like leach pit toilet (LPT).

$$EM_{CO2} = (EM_{CH4} \cdot mol_{CO2}/mol_{CH4}) \quad \text{Eq. (B.24)}$$

where EM_{CH4} are the emissions of CH_4 in g p^{-1} d^{-1} and mol_{CO2} and mol_{CH4} are the molar weights of CH_4 and CO_2 in g mol^{-1}.

By applying Eq. B.1, we extrapolated the daily emissions per person (i.e. EM_{CH4} and EM_{CO2}) to the annual $\dot{m}_{output}$ from the model household (i.e. EmVC1 and EmVC2, respectively). The layer of C was determined by using the molar weights:

$$EmVC2_C = (EmVC2_G \cdot mol_C/mol_{CO2}) \quad \text{Eq. (B.25)}$$

Exemplary for CO_2 emissions where mol_{CO2} and mol_C are the molar weights of CO_2 and C in g mol^{-1}.

Subsequently, we determined the **total gaseous EmV** (EmV_G):

$$EmV_G = EM_{CO2,G} + EM_{CH4,G} \quad \text{Eq. (B.26)}$$

Exemplary for the layer of G; the C-layer was calculated accordingly; N- and P-layer were 0.

II. Liquid emissions from the conventional systems analysed in S1 and S4

In sum, liquid emissions from the conventional systems in S1 and S4 included NH_4^+ and PO_4^{3-}, as nutrient emissions, and H_2O, as the main effluent stream. Groundwater contamination caused by nitrate leaching is frequently observed downstream of latrines (Graham and Polizzotto, 2013). N emits from the latrine as NH_4^+ and then further nitrifies to NO_3^- in aerobic unsaturated sediments in the soil (Wilhelm et al., 1994). Graham and Polizzotto (2013) identified various factors influencing the travel distance of nitrate, including soil structure, and found that the average distance between latrines and the spots where nitrate was detected is 1–25 m.

In S1, we assumed that 18 ± 5 % of the total N contained in all $\dot{m}_{input}$ (i.e. SS1) would be transferred to the remaining sludge (i.e. $tc_{SS1,N}$). Therefore, we calculated that the effluents (i.e. $tc_{EmE,N}$) would contain 82 ± 9% of total N, which consequently emits via leaching. This corresponds with Montangero (2006) and Montangero and Belevi (2007) who assumed that 73–91 % of total N leaches as NH_4^+. Jacks et al. (1999) estimated that deep leaching of nitrate ranges from 1–50 % of total N in sludge. For the septic system analysed in S4, we assumed that 9 ± 4.5 % of total N remains in the sludge and 91 ± 4.5 % of total N emits, based on data from literature. In our model, liquid emissions of **NH_4^+ in the effluent** ($EmEN_G$) were determined, first, on the N-layer (Eq. B.28) and then on the layer of G (Eq. B.29); the layers of C and P were 0.

$$EmEN_N = SS1_N \cdot tc_{EmE,N} \quad \text{Eq. (B.27)}$$

$$EmEN_G = (EmEN_N \cdot mol_{NH4}/mol_N) \quad \text{Eq. (B.28)}$$

where tc is the transfer coefficient and mol_{NH4} and are the molar weights of NH_4^+ and N.

Furthermore, PO_4^{3-} possibly emits from the pit together with the effluent. According to Graham and Polizzotto (2013), PO_4^{3-} act conservative and mainly remains in the sludge residues. If PO_4^{3-} leaches, it is rather immobile and probably leaches into the mineral soil around the pit, not into the groundwater (*ibid.*). Given the local Andosol's high P-fixation (Chesworth, 2008), we assumed that PO_4^{3-} remains in the soil surrounding the pit. Thus, PO_4^{3-} rather emits to the pedosphere than to the hydrosphere. Based on data from literature, we assumed that 72 ± 7 % of total P would be transferred in the effluent (i.e. $tc_{EmE,P}$). We estimated the $\dot{m}_{output}$ of liquid emissions of **PO_4^{3-} in the effluent** ($EmEP_G$) in compliance with the same principle as for NH_4^+ emissions:

$$EmEP_P = SS1_P \cdot tc_{EmE,P} \quad \text{Eq. (B.29)}$$

$$EmEP_G = (EmEN_P \cdot mol_{PO4}/mol_P) \quad \text{Eq. (B.30)}$$

where mol_{PO4} is the molar weight of PO_4^{3-} and mol_P is that of P.

The calculation of **H_2O in the effluent** was slightly more complicated. First, we calculated the total input of H_2O into the pit, which is the sum of H_2O contained in each $\dot{m}_{input}$ (Eq. B.32). Then, we estimated the total input of Dry Matter (DM) to the pit (Eq. B.33) and the total DM remaining in the sludge in the pit (SS2) *after* gaseous and liquid emissions have escaped, which have already been quantified (Eq. B.34). From literature, we deduced a reference value for the water content in toilet sludge ($c_{H2O,SS2}$), with which we finally calculated the $\dot{m}_{output}$ of H_2O in the effluent ($EmEH_G$) on the layer of G (Eq. B.35+B.36). We assumed the layer of C to be 0, whilst N and P emissions have already been calculated separately.

$$SS1_{H2O} = F_{H2O} + U_{H2O} + W1_{H2O} + W2_{H2O} + W3_{H2O} \quad \text{Eq. (B.31)}$$

$$SS1_{dry} = F_{dry} + U_{dry} \quad \text{Eq. (B.32)}$$

$$SS2_{dry} = SS1_{dry} - EmV_G - EmEN_G \quad \text{Eq. (B.33)}$$

$$SS2_{H2O} = \left(c_{H2O,SS2} \cdot SS2_{dry}\right)/\left(1 - c_{H2O,SS2}\right) \quad \text{Eq. (B.34)}$$

$$EmEH_G = SS1_{H2O} - SS2_{H2O} \quad \text{Eq. (B.35)}$$

Note: W3 = flush water was only considered in calculations of S4; all other terms were equivalent in S1 and S4.

Finally, we calculated the $\dot{m}_{output}$ of **total liquid emissions via effluent** (EmE_G):

$$EmE_G = EmEN_G + EmEP_G + EmEH_G \quad \text{Eq. (B.36)}$$

Exemplary shown for the layer of G; the N- and P-layers were calculated accordingly. C-layer was 0.

III. Gaseous emissions from the ecological sanitation systems analysed in S2 and S3

When using a UDDT, initial emissions occur during the **collection of urine** (Jönsson, 2001; Meinzinger, 2010; Montangero et al., 2004). N emits via ammonia volatilisation from the urine collection pipe system (i.e. $NH_4 \rightarrow$ **NH_3**) with 3 ± 1 % of total N ($tc_{EmVN1,N}$) contained in the "urine collected I" ($U2_G$), which is transferred to the gaseous emissions ($EmVN1_G$):

$$EmVN1_N = U2_N \cdot tc_{EmVN1,N} \quad \text{Eq. (B.37)}$$

$$EmVN1_G = (EmVN1_N \cdot mol_{NH3}/mol_N) \quad \text{Eq. (B.38)}$$

where mol_{NH3} is the molar weight of NH_3 and mol_N is that of N. Emissions on the layer of C and P are 0.

Consequently, urine entering the storage facility (i.e. "urine collected II"; $U4_G$) shows a reduced N-content:

$$U4_G = U2_G - EmVN1_G \quad \text{Eq. (B.39)}$$

Exemplary for the layer of G; the C-, N-, P-layers were calculated accordingly.

Further emissions occur during the **storage of urine** and include NH_3 (Jönsson, 2001; Meinzinger, 2010; Montangero et al., 2004) and CH_4 (Londong, 2015). These were calculated similarly to the emissions from urine collection. We assumed ammonia volatilisation from urine storage ($EmVN2_N$) via **$NH_4 \rightarrow NH_3$** to be 2 ± 1 % of the total N ($tc_{EmVN2,N}$) contained in the "urine collected II" ($U4_N$):

$$EmVN2_N = U4_N \cdot tc_{EmVN2,N} \quad \text{Eq. (B.40)}$$

$$EmVN2_G = (EmVN2_N \cdot mol_{NH3}/mol_N) \quad \text{Eq. (B.41)}$$

where mol_{NH3} is the molar weight of NH_3 and mol_N is that of N. Emissions on the layer of C and P were 0.

We assumed C volatilisation from urine storage via $\mathbf{CH_4}$ ($EmVC1_C$) to be 1.0 ± 0.3 % of total C ($tc_{EmVC1,C}$) contained in the "urine collected II" ($U4_C$):

$$EmVC1_C = U4_C \cdot tc_{EmVC1,C} \quad \text{Eq. (B.42)}$$

$$EmVC1_G = (EmVC1_N \cdot mol_{CH4}/mol_C) \quad \text{Eq. (B.43)}$$

where mol_{CH4} is the molar weight of CH_4 and mol_C is that of C. Emissions on the layer of N and P were 0.

In addition, emissions from the **storage and collection of solids** included NH_3, CO_2, CH_4, and H_2O from drying faeces. For the urine that was collected together with the solids due to incomplete urine diversion (U3), we assumed that ammonia volatilisation from the storage and dehydration of solids via $\mathbf{NH_4 \rightarrow NH_3}$ (EmVN3) was $tc_{EmVN3,N} = tc_{EmVN2,N}$:

$$EmVN3_N = U3_N \cdot tc_{EmVN3,N} \quad \text{Eq. (B.44)}$$

$$EmVN3_G = (EmVN3_N \cdot mol_{NH3}/mol_N) \quad \text{Eq. (B.45)}$$

where mol_{NH3} is the molar weight of NH_3 and mol_N that of N. Emissions on the layer of C and P were 0.

Due to data gaps for C emissions from UDDTs, we assumed the processes of biochemical degradation of solid matter - mainly of the easy degradable faeces - to be equivalent to open defecation (Winrock, 2008). In general, emissions from a UDDT depend on the amount of ashes that are used as part of the dry matter toilet additives (Chaggu, 2004). The addition of ashes raises the pH and a pH > 7 can suppress biodegradation of faeces, i.e. avoid CO_2 and CH_4 emissions, but promote ammonia losses (*ibid.*). Nevertheless, we considered emissions from biochemical degradation in our model because, in the CaSa-approach, sawdust and soil were mainly used as dry matter toilet additives with only minor contribution of ash (Section B.2.2.I).

We derived EF for the daily $\mathbf{CH_4}$ emitted per person (EM_{CH4}) from Winrock (2008) and applied Eq. B.24. Subsequently, we calculated the corresponding EF for $\mathbf{CO_2}$ (EM_{CO2}), according to the same approach as explained in Section B.2.3.I and by applying Eq. B.25. Both EM_{CH4} and EM_{CO2} were extrapolated to the model household by applying Eq. B.1 to receive $\dot{m}_{output}$ of CH_4 (EmVC2) and CO_2 (EmVC3). The layer of C in those $\dot{m}_{output}$ was determined by using the molar weights (e.g. Eq. B.26). Then, we calculated the **evaporated $\mathbf{H_2O}$** (EmVH1) from drying faeces (Eq. B.47). For this, we first calculated the total H_2O contained in $\dot{m}_{input}$ of solids collected in the UDDT ($F2_{H2O}$; Eq. B.48).

$$\mathrm{F2_{H2O}} = \mathrm{F1_{H2O}} + \mathrm{U3_{H2O}} + \mathrm{DM_{H2O}} \quad \text{Eq. (B.46)}$$

$$\mathrm{EmVH1_G} = \left[\mathrm{F2_{H2O}} - c_{H2O,F3} \cdot (\mathrm{F2_G} - \mathrm{EmVN3_G} - \mathrm{EmVC2_G} - \mathrm{EmVC3_G})\right]/\left(1 - c_{H2O,F3}\right) \quad \text{Eq. (B.47)}$$

Chien et al. (2001) and Muspratt et al. (2014) provided reference values for the water content ($c_{H2O,F3}$) in "solids after storage in the UDDT" (F3). In addition, we determined the water content of stored solids from the UDDT used in the CaSa-pilot project, as part of a series of experiments that we conducted in Karagwe in March 2015. For approximately three weeks, we took randomised mixed samples from solids stored in the UDDT, with a replication of n = 5. We measured the weight of the samples before and after drying the matter in a laboratory oven for 72 hours at 65° C. Then, we calculated the mean value of the literature references and the field-measured values and used those for computing. Finally, we calculated the total $\dot{m}_{output}$ of gaseous emissions of volatilisation from the UDDT (EmV1):

$$EmV1_G = EmVN1_G + EmVN2_G + EmVN3_G + EmVC1_G + EmVC2_G + EmVC3_G + EmVH1_G \quad \text{Eq. (B.48)}$$

Exemplary shown for the layer of G; the C- and N-layers were calculated accordingly. P-layer was 0.

We assumed that liquid EmE did not exist in sanitation systems using a UDDT.

IV. Gaseous emissions from the sanitation oven analysed in S3

In alternative S3, we additionally analysed the operation of the sanitation oven. Here, further emissions occurred including (i) evaporated H_2O from dehydration of solids during the heat exposure and (ii) emissions from the energy conversion processes within the microgasifier stove.

According to Lehmann and Joseph (2009), the volatilisation temperature of C, N, and P are above the given treatment temperature (i.e. 60–70° C). To simplify, we did not consider gases dissolving in the evaporated water from treated solids. We assumed that in the given thermal conditions, CH_4 or N_2 would not be dissolved. We also neglected emissions of substances that are easier dissolvable, including CO_2 or NH_4/NH_3. The reason is that in the laboratory procedure for determining, for example, Kjeldahl-N, samples should be dried at 75° C (cf. DIN EN 13654 (2001) and DIN EN 13040 (2008)), which would not be advised if high ammonia volatilisation was expected in these conditions. Thus, we concluded that ammonia volatilisation could also be neglected during pasteurisation. However, if in practice too much ash was added and caused a rise in pH, then, ammonia emissions would more likely occur, particularly from urine collected with solid materials.

The loss of water through evaporation during pasteurisation was determined in an experiment conducted on-site in March 2015. We measured the pot of solids collected in the UDDT *before* and *after* the treatment in the sanitation oven. The weight difference was ascribed to evaporated water. The experiment was conducted with a replication of n = 3. We found that during pasteurisation, 2.4 ± 0.6 % of the total FM of solids were lost *before* the treatment ($tc_{EmVH2,G}$), which we completely attributed to **evaporated water** ($EmVH2_G$).

$$EmVH2_{H2O} = EmVH2_G = F3_G \cdot tc_{EmVH2,G} \quad \text{Eq. (B.49)}$$

Emissions on the layer of C, N, and P were 0.

Emissions from the energy conversion process originate directly from complete oxidation of wood gas, which forms through decomposition of the biomass fuel used in the microgasifier. In addition, firewood is combusted, i.e. it is directly and completely oxidised. Appendix A (Sections A.2.3.II and A.2.3.III) describes the applied stoichiometry for modelling the energy conversion processes and the equations for determining the arising emissions from the microgasifier.

The emissions from the sanitation oven comprise CO_2, H_2O, N_2, NO, and SO_2 and were summarised as **volatile emissions from fuel (EmVFu)**. In sum, we quantified two $\dot{m}_{output}$: (i) from the oxidation of wood gas, derived from decomposition of sawdust ($EmVFu1_G$) and (ii) from the oxidation of firewood used as firing sticks ($EmVFu2_G$). In addition, the combustion of fuel requires oxygen, which ambient air provides (Section B.2.2.II). After passing through the microgasifier, the remaining air (i.e. mainly N_2) emits back to the atmosphere. Appendix A Sections A.2.3.II and A.2.3.III) describes the assumed stoichiometric and applied equations to estimate the corresponding $\dot{m}_{export}$ of air after oxidation of fuel 1 and fuel 2 (i.e. $Ao1_G$ and $Ao2_G$).

Finally, we calculated the **total EmV** ($EmV2_G$) processes in the sanitation oven in S3:

$$EmV2_G = EmVH2 + EmVFu1_G + EmVFu2_G + Ao1_G + Ao2_G \quad \text{Eq. (B.50)}$$

Exemplary shown for the layer of G; the C- and N-layers were calculated accordingly. P-layer was 0.

B.2.4. Storage flows

I. Sludge stored in the conventional systems analysed in S1 and S4

We considered the $\dot{m}_{storage}$ of sludge stored in the pit in S1 and in the pit or tank in S4 ($SS2_G$) to be the difference of total $\dot{m}_{input}$ (i.e. SS1) and $\dot{m}_{output}$ (i.e. gaseous and liquid emissions):

$$SS2_G = SS1_G - EmV_G - EmE_G \quad \text{Eq. (B.51)}$$

Exemplary for the layer of G; the C-, N-, P-layers were calculated accordingly.

II. Precipitation in urine storage in the ecological sanitation systems analysed in S2 and S3

According to Londong (2015), about 20 ± 6 % of the total P contained in collected urine is lost during storage because of incrustations and precipitation of P in the storage receptacles.

The $\dot{m}_{storage}$ of P (PS_P) was calculated by using the given coefficient ($tc_{PS,P}$) for P transferred to the urine storage:

$$PS_P = PS_G = U4_P \cdot tc_{PS,P} \quad \text{Eq. (B.52)}$$

Emissions on the layer of C and N were 0.

B.2.5. Output flows: residues from the ecological sanitation systems

I. Stored urine and dried (S2) or sanitised (S3) solids

The $\dot{m}_{output}$ of "urine after storage in UDDT" ($U5_G$) was estimated with:

$$U5_G = U4_G - EmVC1_G - EmVN2_G - PS_G \quad \text{Eq. (B.53)}$$

Exemplarily shown for the layer of G; the C-, N-, P-layers were calculated accordingly.

The $\dot{m}_{output}$ of dried "solids after storage in UDDT" ($F3_G$) was estimated with:

$$F3_G = F2_G - EmVC2_G - EmVC3_G - EmVN3_G - EmVH_G \quad \text{Eq. (B.54)}$$

Exemplarily shown for the layer of G; the C-, N-, P-layers were calculated accordingly.

In alternative S2, $F3_G$ was the final $\dot{m}_{output}$ of "dried solids" available for recycling, whilst in alternative S3, $F3_G$ was the material flow transferred to the sanitation oven. Then, the final $\dot{m}_{output}$ of "sanitised solids" was determined with:

$$F4_G = F3_G - EmVH2_G \quad \text{Eq. (B.55)}$$

Exemplarily shown for the layer of G; the C-, N-, P-layers were calculated accordingly.

II. Ash and char as residues from sanitation oven in S3

According to the pilot technology tested in the case study, two $\dot{m}_{output}$ of residues are available after operating the sanitation oven: (i) ash and char particles remaining inside the stove after gasification of sawdust ($Fu1_G$) and (ii) ash left over from oxidation of firewood ($Fu2_G$). We determined the $\dot{m}_{output}$ of residues available after gasification of sawdust ($R1_G$) by using the transfer coefficient ($tc_{R1,G}$) taken from the analysis of the MES (Table A.12 in Appendix A):

$$R1_G = Fu1_G \cdot tc_{R1,Fu1} \quad \text{Eq. (B.56)}$$

The $\dot{m}_{output}$ of residues available after oxidation of firewood ($R2_G$) was determined by using the ash content in firewood ($c_{ash,Fu2}$) from the literature review of the MES analysis (Table A.12 in Appendix A):

$$R2_G = Fu2_G \cdot c_{ash,Fu2} \quad \text{Eq. (B.57)}$$

Elemental concentrations of C and N in ash and char were also taken from data collected for the MES analysis (Table A.12 in Appendix A). The $\dot{m}_{output}$ of C and N (i.e. $R1_C$ and $R1_N$) was determined by applying the adjusted Eq. B.14. Equivalent to the MES-model, we assumed that total C and N contained in firewood are completely emitted during oxidation, hence $R1_C = R1_N = 0$. Furthermore, we assumed that total P is directly transferred from fuel to residue and thus defined $R1_P = Fu1_P$ and $R2_P = Fu2_P$.

We calculated the sum of residues with:

$$R_G = R1_G + R2_G \quad \text{Eq. (B.58)}$$

Exemplarily shown for the layer of G; the C-, N-, P-layers were calculated accordingly.

III. Waste water from anal cleansing

The $\dot{m}_{output}$ of "waste water from anal cleansing" was equivalent to the $\dot{m}_{input}$ of "cleansing water" because we assumed the direct transfer of cleansing water to the soil filter through the UDDT, without considering processes in the filter thereafter. Hence, the total $\dot{m}_{input}$ is subsequently available for watering flowers or other horticultural plants in the surroundings of the toilet whose roots access the soil in the filter.

B.3. Assessment of emissions to the environment

B.3.1. Assessment of greenhouse gas emissions

Finally, we estimated the greenhouse gas (GHG) emissions in compliance with the procedure of the IPCC and using GWP-factors published by Myhre (2013). We used GWP_{100}-factors[6] (Table B.5) and multiplied these with the quantified $\dot{m}_{output}$ of emission components, which are specifically relevant in terms of climate change.

Table B.5: The GWP-factors used in this analysis; according to Myhre (2013).

Emission component	GWP_{100}-factor	Source
CO_2	1	Table 8.A.1 in Myhre, 2013
CH_4	28	Table 8.A.1 in Myhre, 2013
NO	-11	Table 8.A.3 ("global") in Myhre, 2013

The unit of the factor is kg CO_2e kg^{-1}.

We determined the total GHG emissions of a single MSS-alternative by summing up all emissions of CH_4, CO_2, and NO valued with their respective GWP_{100}-factors and expressed in CO_2-equivalents per household and year [kg CO_2e hh^{-1} yr^{-1}]. Pursuant to Gómez et al. (2006), we included CO_2 emissions from bioenergy use in S3 as information only to determine a possible reduction or increase in GHG emissions between the various alternatives. As already mentioned in the explanations to the MES-model (Appendix A), we did not consider PM emissions in our system analysis due to the lack of appropriate and reliable data from both the case studies and literature.

A.3.1. Assessment of nutrient emissions to the hydrosphere

Liquid emissions of NH_4^+ and PO_4^{3-} as well as gaseous emissions of NO and NH_3 to the atmosphere additionally contribute to environmental emissions that are commonly assessed with the EP. Once in the air, the gases react with sulphuric acid and nitric acid and precipitate in the form of salt, which can easily be relocated to the pedosphere or hydrosphere. In addition, the salts dissolve easily in water, which can lead to an accumulation of nutrients in the water bodies and consequently to excessive growth of plants and algae (i.e. eutrophication).

We estimated the EP pursuant to the procedure of the Institute of Environmental Science at the University of Leiden published by Heijungs et al. (1992) and Guinée (2002). For this, we used the EP-factors (Table B.6) and multiplied these with the quantified material flows of emission components, which are specifically relevant in terms of eutrophication.

Table B.6: The EP-factors used in this analysis; according to Heijungs et al. (1992) and Guinée (2002).

Emission component	EP-factor
total P (to water)	3.07
total N (to water)	0.42
NO	0.13
NH_3	0.35

The unit of the factor is kg PO_4e kg^{-1}.

We determined the total EP of a single alternative by summing up the specific emissions that we assessed with the respective EP-factors. The EP is expressed in PO_4-equivalents per household and year [kg PO_4e hh^{-1} yr^{-1}].

[6] GWP for a time horizon of 100 years (Myhre, 2013).

B.4. DATA EVALUATION

B.4.1. Plausibility criteria

As part of the data evaluation, we chose a set of plausibility criteria for crosschecking estimated values from our model with reliable data from literature sources. We discuss this comparison of the results from our model with the plausibility criteria in the main manuscript (Section 4.1.).

Table B.7: List of plausibility criteria used for evaluation of estimated results from system analysis.

Alternative	Criteria	Source
S1, S4	C-transfer to residues (in pit)	Meinzinger, 2010
S2, S3	C-transfer to residues (in UDDT)	Chaggu, 2004
S2, S3	N-transfer to residues (in UDDT)	Hotta and Funamizu, 2006
S2, S3	total nutrients in excreta (input to toilet)	Jönsson and Vinneras, 2004; Richert et al., 2010

We would like to add another thought on the finding that the estimated C losses via CH_4 and CO_2 emissions in S1 and S4 might be slightly underestimated. We estimated that sludge of S1 and S4 still contained 0.79 ± 0.21 % and 0.61 ± 0.14 % of total C input, respectively, whilst Meinzinger (2010) accounted that ≈ 43 % of C are transferred into the latrine's sludge. However, our estimations of total gaseous emissions represent mean values of two approaches found in literature (Table B.4). When comparing the single sub-alternatives S1_1 and S1_2, we observed that, in line with Reid et al. (2014a), approximately 66 % of C remained in the latrine's sludge, whilst the estimations of Doorn et al. (2006) resulted in ≈ 91 % of C being transferred to sludge. For alternative S4, the observed variation in the analysed sub-alternatives was even higher; the total input C remaining in toilet sludge ranged from ≈ 18 % to ≈ 92 % and ≈ 97 % for S4_4 (after Doorn et al. (2006), with MCF = 0.5 for septic tank), S4_3 (after Doorn et al. (2006), with MCF = 0.1 for pit latrine) and S4_5 (after field-measurements of Winrock (2008), with septic tank assumed similar to a leach pit toilet), respectively. Overall, we conclude that results quantifying gaseous emissions from sanitation systems are characterised by high variance and uncertainty and depend on (i) the assumptions made to describe the system and (ii) the selection of available scientific approaches and data.

B.4.2. Residues from the sanitation oven: model estimations versus field-measurements

As explained above (see Section B.2.5), two kinds of fuels were used in the microgasifier. Sawdust was the main fuel, which is thermo-chemically converted into wood gas and ash and char as solid residues. Firewood was used additionally to enhance the firepower of the microgasifier. To simplify, we assumed that the firewood was completely oxidised, providing only ash as residue. The $\dot{m}_{output}$ of ash was estimated using the ash content in firewood (Eq. B.58).

Results of the modelling based on these assumptions revealed that, per year in the model household, roughly 14.1 ± 4.0 kg ash and char are available after gasification of sawdust and 1.2 ± 0.5 kg ash are available after combustion of firewood. In sum, residues from the sanitation oven comprised 15.3 ± 4.0 kg ash and char.

Furthermore, we conducted an experiment with the sanitation oven on-site in the CaSa-pilot project to collect field-measured data. Therein, we also measured the provision of ash and char as residues after operating the sanitation oven. During the data evaluation of the experiment, we found that, on average, 0.06 ± 0.01 g of ash and char per each gram of solids that were treated (i.e. $g_{residues}\ g^{-1}{}_{solids}$) remained, which equates the matter of residues to 20 ± 2 % of the FM of both sawdust and firewood (i.e. $g_{residues}\ g^{-1}{}_{fuels}$). Using these field-measured parameters, we estimated that the total potentially available residues amount to 30.7 ± 0.7 kg of ash and char per household and year. We conclude that the simplifying assumption that firewood was completely oxidised underestimated the total provision of residues. In other words: **In practice, the recycling potential could be twice as high than estimated in our model.**

B.4.3. Uncertainty check of estimated results from modelling according to error propagation statistics

After modelling in Excel (i.e. *before* data reconciliation in STAN), most flows of the MSS-model had a relative uncertainty (RU) of ± 30 %, which is classified as low according to Laner et al. (2013). Nevertheless, there were some flows that showed average (± 50 %) or high (> 90 %) uncertainty, on which we comment in Table B.8.

Table B.8: Annotated list of flows of the MSS with average or high uncertainty.

Alternative	Flow	RU	Comment
S1-S4	C, N, P in faeces	40-50 %	RU derived from literature review, still classified as adequate.
S1, S4	C, N, P in disposed grey water	40-70 %	RU derived from literature review. Flow was not of particular interest for our work, as domestic grey water was not considered as a recycling flow but deposited partly to the pit or tank. However, these flows contributed to nitrate and phosphate losses via leaching. Compared to the C and nutrient input from urine and faeces, grey water contributed to only about 1-4 % of the total input of these substances and, thus, was of minor importance when assessing the environmental impacts of sanitation technologies through leaching to the pedo- and hydrosphere.
S1, S4	Sludge stored in the pit	50-210 % (S1); > 1000 % (S4)	The high to very high RU of this storage flow is a result of subtraction applied for calculating the values, which can result in high to very high uncertainties (i.e. inherent problem challenging error propagation statistics, see e.g. FAU physics, n.d.).
S2, S3	Gaseous emissions from urine storage (CH_4 and NH_3)	≈ 50 %	RU derived from literature review, still classified as adequate.
S2, S3	P deposited in urine storage	45 %	RU derived from literature review, still classified as adequate.
S2, S3	Gaseous emissions from collection and storage of solids (NH_3)	52 %	RU derived from literature review, still classified as adequate.
S2, S3	P in dry material	43 %	RU derived from literature review, still classified as adequate.
S2, S3	Evaporated water from drying of faeces in the UDDT	42 %	RU derived from computing a complex term including subtractions, which can result in rising uncertainties. However, RU can still be classified as adequate
S3	Evaporated water from dehydration of faeces during sanitation process in the oven	45 %	RU derived from computing a complex term including subtractions, which can result in rising uncertainties. However, RU can still be classified as adequate.
S3	N and P in sawdust and firewood	44-56 %	RU derived from (i) error propagation of preceding flows modelled for the UDDT and (ii) from literature review. However, RU can still be classified as adequate.
S3	Import and export of ambient air (i.e. Ai1, Ai2, Ao1, Ao2)	40-100 %	Elevated RUs were generally acceptable here, as flows are not highly relevant because air is not a limited resource. RU resulted from subtraction of flows and was highest for N. Nevertheless, when combining the flows (Ai = Ai1 + Ai2 and Ao = Ao1 + Ao2), the RU was adequate with < 50 %.
S3	Emissions from fuel 1 on the layer of C and N	≈ 70 %	RU derived from (i) error propagation of preceding calculations modelling the decomposition of elements contained in sawdust and (ii) from subtractions as part of the calculation. However, RU can still be classified as adequate or slightly high. Furthermore, when combining the emission flows from both fuels (EmV = EmFU1 + EmFu2 + Ao1 + Ao2) then the RU was adequate with < 50 %.
S3	C, N, P in residues from sanitation oven/microgasifier	55-66 %	RU derived from error propagation of preceding calculations modelling the required fuel based on the input of solids quantified in the UDDT-model. However, RU can still be classified as adequate or slightly high.

B.5. COLLECTED DATA

To determine the mean values of material characteristics and process variables, we collected data from:

- Literature review.
- Accessing project data of case studies including:
  - Soil and material samples collected within the CaSa-project (J. Alexander, I. Bamuhiga, A. Bitakwate, A. Krause, D. Vedasto, and others) and analysed at the department of soil science at TU Berlin (J. Geffers, A. Krause, and others) from 2012-2014;
  - Teamwork and discussions with the CaSa-team about experiences from the pilot project;
  - Project files documenting the daily routines in the pilot project including material uses etc.;
  - Experiment with the sanitation oven to collect field-measured data on fuel consumption, loss of weight through evaporation and provision of residues, as conducted by the CaSa-team (J. Alexander, A. Bitakwate, A. Krause) in Karagwe in 2015.
- Auxiliary calculations relevant for modelling included:
  - Determining the mean value of moisture in faeces and solid material when it leaves the UDDT, from data provided by Chien et al., 2001, and by an experiment conducted in Karagwe in March 2015;
  - Determining the mean value of moisture in faecal sludge in a pit latrine, from data provided by Bakare et al., 2012, Buckeley et al., 2008, Chaggu, 2004, Muspratt et al., 2014;
  - Determining the mean value of specific parameters when operating the sanitation oven from CaSa-pilot project, from values recorded in an experiment conducted in Karagwe in March 2015 (e.g. fuel consumption, residues of ash and char, evaporated water, etc.);
  - Determining density, moisture content, C-, N-, P-concentrations in FM of the mix of dry material used in the UDDT, based on data from CaSa, 2015, Chaggu, 2004, Venkataraman et al., 2004, Krause et al., 2016.

Table B.9 summarizes all parameter values that we used in the MSS-model.

Table B.9: List of material characteristics and other parameter values for the MSS-model obtained from data collection and literature review.

Name	Unit		Δx	RU	Sources	Spatial context
Loads of and nutrient concentrations in human excreta						
Faeces:						
Volume	$dm^3\ p^{-1}\ d^{-1}$	0.28	± 0.09	34 %	Calculation with assumed mass and density	Africa
Mass	$g\ p^{-1}\ d^{-1}$	250	± 80	32 %	Assumption, based on Berger, 2008; Chaggu, 2004; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Ethiopia, Europe, Tanzania, Uganda
Density	$kg\ FM\ dm^{-3}$	0.9	± 0.1	11 %	Assumption, based on CaSa, 2015; Meinzinger, 2010	Ethiopia, Europe, Tanzania
DM content	% FM	0.25	± 0.09	36 %	Assumption, based on CaSa, 2015; Chaggu, 2004; Meinzinger, 2010	Ethiopia, Europe, Tanzania
Water content	% FM	0.75	± 0.09	12 %	Assumption, based on CaSa, 2015; Chaggu, 2004; Meinzinger, 2010	Ethiopia, Europe, Tanzania
OM content	% DM	0.92	± 0.05	5 %	Assumption, based on Berger, 2008; CaSa, 2015; Chaggu, 2004; Meinzinger, 2010	Ethiopia, Europe, Tanzania
Total C	$g\ p^{-1}\ d^{-1}$	23.1	± 9.5	41 %	Assumption, based on Berger, 2008; CaSa, 2015; Chaggu, 2004; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Ethiopia, Europe, Tanzania, Uganda
Total N	$g\ p^{-1}\ d^{-1}$	1.4	± 0.7	50 %	Calculation, based on FAO, n.d.; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Meinzinger, 2010; Montangero, 2006	Ethiopia, Europe, Tanzania, Uganda
Total P	$g\ p^{-1}\ d^{-1}$	0.4	± 0.2	49 %	Calculation, based on FAO, n.d; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Meinzinger, 2010; Montangero, 2006	Ethiopia, Europe, Tanzania, Uganda, Vietnam
Urine:						
Volume	$dm^3\ p^{-1}\ d^{-1}$	1.1	± 0.2	18 %	Assumption, based on Berger, 2008; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Ethiopia, Europe, Uganda
Mass	$g\ p^{-1}\ d^{-1}$	1128	± 205	18 %	Calculation	
Density	$kg\ dm^{-3}$	1.0	-		Assumption, based on UPB, n.d.	Germany
DM content	% FM	0.04	± 0.03	75 %	Assumption, based on Chaggu, 2004; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Ethiopia, Tanzania, Uganda
Water content	% FM	0.96	± 0.03	3 %	Assumption, based on Chaggu, 2004; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Ethiopia, Tanzania, Uganda
OM content	% DM	0.75	± 0.10	13 %	Assumption, based on Chaggu, 2004	Tanzania
Total C	$g\ p^{-1}\ d^{-1}$	8.8	± 3.1	35 %	Assumption, based on Berger, 2008; CaSa, 2015; Chaggu, 2004; Jönsson and Vinnerås, 2004; Meinzinger, 2010	Europe, Ethiopia, Tanzania, Uganda
Total N	$g\ p^{-1}\ d^{-1}$	5.7	± 0.7	13 %	Calculation, based on FAO, n.d; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Meinzinger, 2010; Montangero, 2006	Europe, Ethiopia, Tanzania, Uganda, Vietnam
Total P	$g\ p^{-1}\ d^{-1}$	0.7	± 0.2	33 %	Calculation, based on FAO, n.d; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Meinzinger, 2010; Montangero, 2006	Europe, Ethiopia, Tanzania, Uganda, Vietnam
Waste water management						
Fresh water use:						
Private water use	$dm^3\ p^{-1}\ d^{-1}$	105	± 26	25 %	Data analysis of Meinzinger, 2010	Europe
Private water use	$dm^3\ p^{-1}\ d^{-1}$	6	± 3	50 %	Assumption of Meinzinger, 2010	low-income countries
For bathing	$dm^3\ p^{-1}\ d^{-1}$	8.0	± 1.5	19 %	Mavuno, 2015; Tumwine et al., 2002	East Africa, Karagwe
For cooking	$dm^3\ p^{-1}\ d^{-1}$	5.0	± 1.0	20 %	Mavuno, 2015; Tumwine et al., 2002	East Africa, Karagwe
For washing clothes	$dm^3\ p^{-1}\ d^{-1}$	1.8	± 0.5	28 %	Mavuno, 2015; Tumwine et al., 2002	East Africa, Karagwe
For washing dishes	$dm^3\ p^{-1}\ d^{-1}$	3.5	± 1.0	29 %	Mavuno, 2015; Tumwine et al., 2002	East Africa, Karagwe
For hand-washing after toilet	$dm^3\ p^{-1}\ d^{-1}$	1.8	± 0.3	14 %	Mavuno, 2015	
Sum of water use	$dm^3\ p^{-1}\ d^{-1}$	20.1	± 2.1	11 %	Calculation	Karagwe
Grey water:						
DM	$g\ p^{-1}\ d^{-1}$	60	± 33	56 %	Data analysis of Meinzinger, 2010	Generic
DM content	% FM	0.001	± 0.0003	61 %	Calculation	
Water content	% FM	0.99	± 0.61	61 %	Calculation	
OM	$g\ p^{-1}\ d^{-1}$	44	± 8	18 %	Assumption, based on Londong, 2015	Generic
Organic C	$g\ p^{-1}\ d^{-1}$	13	± 2	15 %	Assumption, based on Meinzinger, 2010	Generic

Total N	g p^{-1} d^{-1}	1.0	± 0.4	40 %	Assumption, based on Meinzinger, 2010; Londong, 2015	Generic
Total P	g p^{-1} d^{-1}	0.5	± 0.3	60 %	Assumption, based on Meinzinger, 2010; Londong, 2015	Generic
Total C	g dm^{-3}	0.7	± 0.1	18 %	Calculation	
Total N	g dm^{-3}	0.05	± 0.02	41 %	Calculation	
Total P	g dm^{-3}	0.02	± 0.02	61 %	Calculation	
Grey water disposal to pit latrine:						
From bathing	%	0.10	± 0.05	45 %	Mavuno, 2015	Karagwe
From washing clothes	%	0.26	± 0.11	43 %	Mavuno, 2015	Karagwe
Grey water disposal to septic tank:						
From bathing	%	0.30	± 0.10	32 %	Mavuno, 2015	Karagwe
From washing clothes	%	0.08	± 0.05	64 %	Mavuno, 2015	Karagwe
From cleaning dishes	%	0.14	± 0.12	88 %	Mavuno, 2015	Karagwe
Cleansing water use:						
After urination	dm^3 $urination^{-1}$	0.0	-		Assumption, based on Chaggu, 2004; Mavuno, 2015	Karagwe, Tanzania
After defecation	dm^3 $defecation^{-1}$	0.3	± 0.1	20 %	Assumption, based on Chaggu, 2004; Mavuno, 2015	Karagwe, Tanzania
Flush water:						
Flush system	% hh	0.44	± 0.09	20 %	Mavuno, 2015	Karagwe
Pour system	% hh	0.36	± 0.07	20 %	Mavuno, 2015	Karagwe
Other	% hh	0.20	± 0.04	20 %	Mavuno, 2015	Karagwe
Water use with flush system	dm^3 p^{-1} d^{-1}	10	± 3	30 %	Mavuno, 2015; Tumwine et al., 2002	Karagwe
Water use with pour system	dm^3 p^{-1} d^{-1}	6.5	± 1.0	15 %	Mavuno, 2015	Karagwe
Flush water	dm^3 $action^{-1}$	5.0	± 1.0	20 %	Assumption, based on Londong, 2015	Generic
Flush water	action p^{-1} d^{-1}	4.0	± 1.0	25 %	Assumption, based on Londong, 2015	Generic
Flush water	dm^3 p^{-1} d^{-1}	20	± 6	32 %	Calculation, based on Londong, 2015	Generic
Flush water	dm^3 p^{-1} d^{-1}	3.0	± 1.0	33 %	Assumption, based on Mavuno, 2015; Meinzinger, 2010	Ethiopia, Karagwe
					Pit latrine and septic tank: general characteristics and emissions	
Depth of latrine	m	4.0	± 1.0	25 %	Mavuno, 2015	Karagwe
Lined pit latrine as septic tank	% hh	0.56	± 0.11	20 %	Mavuno, 2015	Karagwe
Concrete septic tank	% hh	0.38	± 0.07	20 %	Mavuno, 2015	Karagwe
Plastic septic tank	% hh	0.06	± 0.01	20 %	Mavuno, 2015	Karagwe
Water content in sludge	% FM	0.848	± 0.005	1 %	Calculation, based on Bakare et al., 2012; Buckeley et al., 2008; Chaggu, 2004; Muspratt et al., 2014	Ghana, Senegal, South Africa, Tanzania, Uganda
CH_4 & CO_2 emissions:						
B_0	kg CH_4 kg^{-1} BOD	0.6	± 0.2	30 %	Default value, based on Reid et al., 2014a; uncertainty: Table 6.7 in Doorn et al., 2006	
BOD	kg p^{-1} yr^{-1}	13.5	± 1.8	14 %	Assumption, based on Doorn et al., 2006 (Table 6.4); Reid et al., 2014a; Reid et al., 2014b; error calculated with given uncertainty interval of 12.78–16.43 kg p^{-1} yr^{-1}	Africa
		S1_1) CH_4 & CO_2 emissions:			approach of Reid et al., 2014a	
MCF	-	0.23	± 0.10	43 %	Calculation	Tanzania
EF	kg CH_4 kg^{-1} BOD	0.14	± 0.04	31 %	National average based on Reid et al., 2014a; Reid et al., 2014b; with values for EF taken from Doorn et al., 2006 integrated in high-resolution geospatial analysis with water table Assumption based on Fan et al., 2013; error calculated with given uncertainty interval of 0.116–0.202 kg of CH_4 kg^{-1} BOD	Tanzania
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	1.9	± 0.6	34 %	Calculation, based on Reid et al., 2014a; Reid et al., 2014b	
CH_4 emissions	kg C p^{-1} yr^{-1}	1.4	± 0.5	34 %	Calculation	

CH_4 emissions	g CH_4 p^{-1} d^{-1}	5.1	± 1.7	34 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	3.9	± 1.3	34 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	14.1	± 4.8	34 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	3.9	± 1.3	34 %	Calculation	
Volume CH_4	dm^3 CH_4 p^{-1} d^{-1}	7.1	± 2.4	34 %	Calculation	
Volume CO_2	dm^3 CO_2 p^{-1} d^{-1}	7.1	± 2.4	34 %	Calculation	
		S1_2) CH_4 & CO_2 emissions:			approach of Doorn et al., 2006 (IPCC)	
MCF	-	0.10	± 0.05	50 %	Doorn et al., 2006: MCF in Table 6.3; uncertainty in Table 6.7	
EF	kg CH_4 kg^{-1} BOD	0.06	± 0.02	30 %	Calculation, uncertainty based on Table 6.7 in Doorn et al., 2006;	
U	%	0.6	NA		Assumption, based on Mavuno, 2015 and Doorn et al., 2006; Table 6.5-Kenya	Kenya, Karagwe
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	0.5	± 0.2	33 %	Calculation, based on Doorn et al., 2006	
CH_4 emissions	kg C p^{-1} yr^{-1}	0.4	± 0.1	33 %	Calculation	
CH_4 emissions	g CH_4 p^{-1} d^{-1}	1.3	± 0.4	33 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	1.0	± 0.3	33 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	3.7	± 1.2	33 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	1.0	± 0.3	33 %	Calculation	
Volume CH_4	dm^3 CH_4 p^{-1} d^{-1}	1.9	± 0.6	33 %	Calculation	
Volume CO_2	dm^3 CO_2 p^{-1} d^{-1}	1.8	± 0.6	33 %	Calculation	
		S4_1) CH_4 & CO_2 emissions:			approach of Reid et al., 2014a	
MCF	-	0.23	± 0.11	50 %	Reid et al., 2014a; uncertainty: Table 6.7 in Doorn et al., 2006;	Tanzania
EF	kg CH_4 kg^{-1} BOD	0.14	± 0.04	31 %	based on Doorn et al., 2006; Reid et al., 2014a; Reid et al., 2014b	Africa
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	1.9	± 0.6	34 %	Calculation, based on Reid et al., 2014a; Reid et al., 2014b	
CH_4 emissions	kg C p^{-1} yr^{-1}	1.4	± 0.5	34 %	Calculation	
CH_4 emissions	g CH_4 p^{-1} d^{-1}	5.1	± 1.7	34 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	3.9	± 1.3	34 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	14.1	± 4.8	34 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	3.9	± 1.3	34 %	Calculation	
		S4_2) CH_4 & CO_2 emissions:			approach of Reid et al., 2014a	
MCF	-	0.50	± 0.25	50 %	Reid et al., 2014a for septic tank; MCF: Table 6.3; uncertainty: Table 6.7	Tanzania
EF	kg CH_4 kg^{-1} BOD	0.30	± 0.09	30 %	Calculation; uncertainty based on Table 6.7 in Doorn et al., 2006;	Africa
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	4.1	± 1.3	33 %	Calculation, based on Reid et al., 2014a; Reid et al., 2014b	
CH_4 emissions	kg C p^{-1} yr^{-1}	3.0	± 1.0	33 %	Calculation	
CH_4 emissions	g CH_4 p^{-1} d^{-1}	11.1	± 3.7	33 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	8.3	± 2.7	33 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	30.5	± 10.0	33 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	8.3	± 2.7	33 %	Calculation	
		S4_3) CH_4 & CO_2 emissions:			approach of Doorn et al., 2006	
MCF	-	0.10	± 0.05	50 %	Doorn et al., 2006; MCF for pit latrine Table 6.3, for uncertainty Table 6.7	
EF	kg CH_4 kg^{-1} BOD	0.06	± 0.02	30 %	Calculation; uncertainty based on Table 6.7 in Doorn et al., 2006	
U	%	0.6	NA		Assumption, based on Mavuno, 2015; Doorn et al., 2006 Table 6.5	Kenya
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	0.5	± 0.2	33 %	Calculation, based on Doorn et al., 2006; Reid et al., 2014a; Reid et al., 2014b	
CH_4 emissions	kg C p^{-1} yr^{-1}	0.4	± 0.1	33 %	Calculation	
CH_4 emissions	g CH_4 p^{-1} d^{-1}	1.3	± 0.4	33 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	1.0	± 0.3	33 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	3.7	± 1.2	33 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	1.0	± 0.3	33 %	Calculation	
		S4_4) CH_4 & CO_2 emissions:			approach of Doorn et al., 2006;	
MCF	-	0.50	± 0.25	50 %	25); MCF for septic tank after Table 6.3; uncertainty: Table 6.7	
EF	kg CH_4 kg^{-1} BOD	0.30	± 0.09	30 %	Calculation; uncertainty based on Table 6.7 in Doorn et al., 2006;	

U	%	0.6	NA		Assumption, based on Mavuno, 2015 and Doorn et al., 2006 Table 6.5	Kenya
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	2.4	± 0.8	33 %	Calculation, based on Doorn et al., 2006	
CH_4 emissions	kg C p^{-1} yr^{-1}	1.8	± 0.6	33 %	Calculation	
CH_4 emissions	g CH_4 p^{-1} d^{-1}	6.7	± 2.2	33 %	Calculation	
CH_4 emissions	g C p^{-1} d^{-1}	5.0	± 1.6	33 %	Calculation	
CO_2 emissions	g CO_2 p^{-1} d^{-1}	18.3	± 6.0	33 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	5.0	± 1.6	33 %	Calculation	
		S4_5) CH_4 & CO_2 emissions:			approach of Winrock, 2008	
CH_4 emissions	kg CH_4 p^{-1} yr^{-1}	0.0005	± 0.0001	30 %	Winrock, 2008	India
CH_4 emissions	g CH_4 p^{-1} d^{-1}	0.5	± 0.1	30 %	Calculation, based on Winrock, 2008	India
CH_4 emissions	g C p^{-1} d^{-1}	0.3	± 0.1	30 %	Calculation, based on Winrock, 2008	India
CO_2 emissions	g CO_2 p^{-1} d^{-1}	1.3	± 0.4	30 %	Calculation, based on Sattler, 2011; Toprak, n.d.	
CO_2 emissions	g C p^{-1} d^{-1}	0.3	± 0.1	30 %	Calculation	
N emissions pit latrine:					assumption: pit is unlined	
N transfer into sludge	% N_{tot}	0.18	± 0.05	30 %	Assumption, based on Jacks et al., 1999 (range of 15-20 % → x=0.183; RU=5%); Montangero, 2006 (range of 9-27 % → x=0.180; RU=50%); Montangero et al., 2004	Botswana, Vietnam
Liquid emissions; NH_4^+	% N_{tot}	0.82	± 0.09	11 %	Montangero, 2006 (73-91 %); Montangero and Belevi, 2007	Botswana, Vietnam
N emissions septic tank:					with assumption of septic tank being a lined pit	
N transfer into sludge	% N_{tot}	0.09	± 0.05	50 %	Montangero, 2006 (.05-0.14 % N)	Vietnam
Liquid emissions; NH_4^+	% N_{tot}	0.91	± 0.05	5 %	Montangero, 2006 (86-95%); Montangero and Belevi, 2007	Vietnam
Neglected gaseous N emissions in both systems:						
N_2	% N_{tot}	0.0	-		Assumption and simplification, based on Montangero, 2006; Montangero and Belevi, 2007	Botswana, Vietnam
NH_3	% N_{tot}	0.0	-		Assumption and simplification, based on Graham and Polizzotto, 2013; Jacks et al., 1999; Montangero and Belevi, 2007	Botswana, Vietnam
N_2O	% N_{tot}	0.0	-		Doorn et al., 2006	Generic
P emissions both systems:						
P transfer to sludge	% P	0.28	± 0.07	25 %	Assumption, based on Meinzinger, 2010 (25-31%;); Montangero, 2006; Montangero and Belevi, 2007 (18-40%;)	Botswana, Ethiopia, Vietnam
Liquid emissions; PO_4^{3-}	% P	0.72	± 0.07	10 %	Calculation	
					UDDT: general characteristics and emissions	
Urine collection rate	% FM	0.85	± 0.05	6 %	Assumption, based on CaSa, 2015; Jönsson, 2001; Jönsson and Vinnerås, 2004; Meinzinger, 2010; Vinnerås and Jönsson, 2002	Generic
Dry material	kg FM p^{-1} d^{-1}	0.13	± 0.02	17 %	Calculation	
Dry material	dm^3 p^{-1} d^{-1}	0.23	± 0.02	9 %	CaSa, 2015	Karagwe
Dry material	kg dm^{-3}	0.58	± 0.08	14 %	Calculation, based on Chaggu, 2004; Krause et al., 2016; Venkataraman et al., 2004	Karagwe, India, Tanzania
DM in dry material	% FM	0.87	± 0.15	18 %	Calculation, based on CaSa, 2015; Krause et al., 2016; data collection MES	
C in dry material	g C kg FM^{-1}	98	± 34	34 %	Calculation, based on Baijukya et al., 1998; Krause et al., 2016 (for soil); data collection MES (for ash, sawdust)	
N in dry material	g N kg FM^{-1}	2.0	± 0.4	20 %	Calculation, based on Baijukya et al., 1998; Krause et al., 2016 (for soil); data collection MES (for ash, sawdust)	
P in dry material	g P kg FM^{-1}	1.2	± 0.5	40 %	Calculation, based on Baijukya et al., 1998; Krause et al., 2016 (for soil); data collection MES (for ash, sawdust)	
C in dry material	g C p^{-1} d^{-1}	13	± 5	38 %	Calculation	
N in dry material	g N p^{-1} d^{-1}	0.3	± 0.1	26 %	Calculation	

P in dry material	g P p^{-1} d^{-1}	0.2	± 0.1	43 %	Calculation	
Water content of solids when leaving UDDT	% FM	0.47	± 0.03	6 %	Calculation, based on Chien et al., 2001; Muspratt et al., 2014	Ghana, Senegal, Uganda, Vietnam
Gaseous emissions from urine:						
NH_3 from collection	% N_{tot}	0.03	± 0.01	33 %	Assumption, based on Jönsson, 2001; Meinzinger, 2010; Montangero et al., 2004	Ethiopia, Uganda, Vietnam
NH_3 from storage	% N_{tot}	0.02	± 0.01	50 %	Assumption, based on Jönsson, 2001; Meinzinger, 2010; Montangero et al., 2004	Ethiopia, Uganda, Vietnam
P transfer into storage	% P	0.20	± 0.06	30 %	Londong, 2015	Generic
CH_4 from storage	% C	0.01	± 0.003	30 %	Londong, 2015	Generic
Gaseous emissions from solids:						
CH_4 emissions	g CH_4 p^{-1} d^{-1}	1.1	± 0.3	30 %	Winrock, 2008	India
CH_4 emissions	g C p^{-1} d^{-1}	0.8	± 0.2	30 %	Winrock, 2008	India
CO_2 emissions	g CO_2 p^{-1} d^{-1}	3.0	± 0.9	30 %	Calculation, based on Sattler, 2011; Toprak, n.d.	Generic
CO_2 emissions	g C p^{-1} d^{-1}	0.8	± 0.2	30 %	Calculation	
Sanitation oven: general characteristics, resource consumption and residue production						
Pot size	dm^3 pot^{-1}	30	± 3	10 %	Based on CaSa, 2015; own experiments, March 2015	Karagwe
Pot filling	g pot^{-1}	15338	± 2541	17 %	Based on CaSa, 2015; own experiments, March 2015	Karagwe
Evaporated water during sanitation	% FM	0.024	± 0.006	27 %	Based on own experiments, March 2015	Karagwe
Fuel 1 (sawdust)	g FM fuel g^{-1} FM solid	0.13	± 0.02	16 %	Based on CaSa, 2015; own experiments, March 2015	Karagwe
Fuel 2 (firewood)	g FM fuel g^{-1} FM solid	0.17	± 0.02	14 %	Based on own experiments, March 2015	Karagwe
Ash and char as residues from SG	wt.-% (FM)	0.213	± 0.02	9 %	From data collection MES	
Plausibility criteria						
C transfer into sludge of pit latrine or septic tank	% C	0.43	± 0.05	12 %	Assumption, based on Wendland, 2009	
CH_4 from UDDT	g CH_4 p^{-1} d^{-1}	0.0			Assumption of Chaggu, 2004	Tanzania
N in excreta (mix)	kg p^{-1} yr^{-1}	4.6	NA		Richert et al., 2010	Generic
N in excreta (mix)	kg p^{-1} yr^{-1}	2.2	NA		Jönsson and Vinnerås, 2004	Uganda
N in stored urine	g dm^{-3}	9.2	NA		Berger, 2008	Generic
P in excreta (mix)	kg p^{-1} yr^{-1}	0.5	NA		Richert et al., 2010	Generic
P in excreta (mix)	kg p^{-1} yr^{-1}	0.3	NA		Jönsson and Vinnerås, 2004	Uganda
P in stored urine	g dm^{-3}	0.5	NA		Berger, 2008	Generic
flush water	dm^3 p^{-1} yr^{-1}	15,000	NA		Winblad and Simpson-Hébert, 2004	Generic

B.6. LIST OF PROCESSES AND FLOWS

Finally, we provide a list of all flows and processes part of the MFA-model for the four alternatives of the MSS as setup in STAN (Table B.10).

Table B.10: List of PR, SPR and flows as implemented in STAN for four alternatives (S1-S4) of the MSS-model

	Process	Flow	Flow name	Source process	Destination process
Alternative S1: PL					
PR: latrine					
Input	PR1.1	F1.1	Faeces	IMPORT	PR1.1, latrine
	PR1.1	U1.1	Urine	IMPORT	PR1.1, latrine
	PR1.1	W1.1	Cleansing water	IMPORT	PR1.1, latrine
	PR1.1	W1.2	Disposal of grey water	IMPORT	PR1.1, latrine
Output	PR1.1	SS1.1	Sludge to store	PR1.1, latrine	SPR1.2.1, pit
PR: pit					
Input	PR1.2	SS1.1	Sludge to store	PR1.1, latrine	SPR1.2.1, pit
Output	PR1.2	EmV1	Sum emission vitalisation	SPR1.2.2, sum EmV	EXPORT
	PR1.2	EmE1	Sum emission effluent	SPR1.2.3, sum EmE	EXPORT
SPR: pit					
Input	SPR1.2.1	SS1.1	Sludge to store	PR1.1, latrine	SPR1.2.1, pit
Output	SPR1.2.1	EmVC1.1	Gaseous emissions; CH4	SPR1.2.1, pit	SPR1.2.2, sum EmV
	SPR1.2.1	EmVC1.2	Gaseous emissions; CO2	SPR1.2.1, pit	SPR1.2.2, sum EmV
	SPR1.2.1	EmEP1	Liquid emissions; PO43-	SPR1.2.1, pit	SPR1.2.3, sum EmE
	SPR1.2.1	EmEN1	Liquid emissions; NH4+	SPR1.2.1, pit	SPR1.2.3, sum EmE
	SPR1.2.1	EmEH1	Effluent; H2O	SPR1.2.1, pit	SPR1.2.3, sum EmE
SPR: sum EmV					
Input	SPR1.2.2	EmVC1.1	Gaseous emissions; CH4	SPR1.2.1, pit	SPR1.2.2, sum EmV
	SPR1.2.2	EmVC1.2	Gaseous emissions; CO2	SPR1.2.1, pit	SPR1.2.2, sum EmV
Output	SPR1.2.2	EmV1	Sum emission vitalisation	SPR1.2.2, sum EmV	EXPORT
SPR: sum EmE					
Input	SPR1.2.3	EmEN1	Liquid emissions; NH4+	SPR1.2.1, pit	SPR1.2.3, sum EmE
	SPR1.2.3	EmEP1	Liquid emissions; PO43-	SPR1.2.1, pit	SPR1.2.3, sum EmE
	SPR1.2.3	EmEH1	Effluent; H2O	SPR1.2.1, pit	SPR1.2.3, sum EmE
Output	SPR1.2.3	EmE1	Sum emission effluent	SPR1.2.3, sum EmE	EXPORT
Alternative S2: EcoSan					
PR: UDDT					
Input	PR2.1	F2.1	Faeces	IMPORT	SPR2.1.1.2, collection of solids
	PR2.1	U2.1	Urine	IMPORT	SPR2.1.1.1, urine division
	PR2.1	DM2	Dry material	IMPORT	SPR2.1.1.2, collection of solids
	PR2.1	W2.1	Cleansing water	IMPORT	SPR2.1.2, filter
Output	PR2.1	U2.5	Urine after storage in UDDT	SPR2.1.3.2, urine storage	EXPORT
	PR2.1	F2.3	Solids after storage in UDDT	SPR2.1.3.3, solids collection & storage	EXPORT
	PR2.1	EmV2	Sum emission vitalisation	SPR2.1.3.4, sum EmV	EXPORT
	PR2.1	W2.2	Waste water from cleansing	SPR2.1.2, filter	EXPORT
SPR: toilet					
Input	SPR2.1.1	DM2	Dry material	IMPORT	SPR2.1.1.2, collection of solids
	SPR2.1.1	U2.1	Urine	IMPORT	SPR2.1.1.1, urine division
	SPR2.1.1	F2.1	Faeces	IMPORT	SPR2.1.1.2, collection of solids
Output	SPR2.1.1	U2.2	Urine collected 1	SPR2.1.1.1, urine division	SPR2.1.3.1, urine collection
	SPR2.1.1	F2.2	Solids collected	SPR2.1.1.2, collection of solids	SPR2.1.3.3, solids collection & storage
SPR: urine division					
Input	SPR2.1.1.1	U2.1	Urine	IMPORT	SPR2.1.1.1, urine division
Output	SPR2.1.1.1	U2.3	Urine mixed with solids	SPR2.1.1.1, urine division	SPR2.1.1.2, collection of solids
	SPR2.1.1.1	U2.2	Urine collected 1	SPR2.1.1.1, urine division	SPR2.1.3.1, urine collection
SPR: collection of solids					
Input	SPR2.1.1.2	F2.1	Faeces	INPUT	SPR2.1.1.2, collection of solids
	SPR2.1.1.2	DM2	Dry material	INPUT	SPR2.1.1.2, collection of solids
	SPR2.1.1.2	U2.3	Urine mixed with solids	SPR2.1.1.1, urine division	SPR2.1.1.2, collection of solids
Output	SPR2.1.1.2	F2.2	Solids collected	SPR2.1.1.2, collection of solids	SPR2.1.3.3, solids collection & storage
SPR: filter					
Input	SPR2.1.2	W2.1	Cleansing water	IMPORT	SPR2.1.2, filter
Output	SPR2.1.2	W2.2	Waste water from cleansing	SPR2.1.2, filter	EXPORT
SPR: collection & storage					
Input	SPR2.1.3	U2.2	Urine collected 1	SPR2.1.1.1, urine division	SPR2.1.3.1, urine collection
	SPR2.1.3	F2.2	Solids collected	SPR2.1.1.2, collection of solids	SPR2.1.3.3, solids collection & storage
Output	SPR2.1.3	U2.5	Urine after storage in UDDT	SPR2.1.3.2, urine storage	EXPORT
	SPR2.1.3	F2.3	Solids after storage in UDDT	SPR2.1.3.3, solids collection	EXPORT

	Process	Flow	Flow name	Source process	Destination process
				& storage	
	SPR2.1.3	EmV2	Sum emission vitalisation	SPR2.1.3.4, sum EmV	EXPORT
SPR: urine collection					
Input	SPR2.1.3.1	U2.2	Urine collected 1	SPR2.1.1.1, urine division	SPR2.1.3.1, urine collection
Output	SPR2.1.3.1	U2.4	Urine collected 2	SPR2.1.3.1, urine collection	SPR2.1.3.2, urine storage
	SPR2.1.3.1	EmVN2.1	Gaseous emissions; NH3	SPR2.1.3.1, urine collection	SPR2.1.3.4, sum EmV
SPR: urine storage					
Input	SPR2.1.3.2	U2.4	Urine collected 2	SPR2.1.3.1, urine collection	SPR2.1.3.2, urine storage
Output	SPR2.1.3.2	U2.5	Urine after storage in UDDT	SPR2.1.3.2, urine storage	
	SPR2.1.3.2	EmVC2.1	Gaseous emissions; CH4	SPR2.1.3.2, urine storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.2	EmVN2.2	Gaseous emissions; NH3	SPR2.1.3.2, urine storage	SPR2.1.3.4, sum EmV
SPR: solids collection & storage					
Input	SPR2.1.3.3	F2.2	Solids collected	SPR2.1.1.2, collection of solids	SPR2.1.3.3, solids collection & storage
Output	SPR2.1.3.3	F2.3	Solids after storage in UDDT	SPR2.1.3.3, solids collection & storage	
	SPR2.1.3.3	EmVC2.2	Gaseous emissions; CH4	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.3	EmVC2.3	Gaseous emissions; CO2	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.3	EmVN2.3	Gaseous emissions; NH3	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.3	EmVH2.1	Drying of faeces	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
SPR: sum EmV					
Input	SPR2.1.3.4	EmVC2.1	Gaseous emissions; CH4	SPR2.1.3.2, urine storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVN2.2	Gaseous emissions; NH3	SPR2.1.3.2, urine storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVN2.1	Gaseous emissions; NH3	SPR2.1.3.1, urine collection	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVC2.2	Gaseous emissions; CH4	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVC2.3	Gaseous emissions; CO2	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVN2.3	Gaseous emissions; NH3	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
	SPR2.1.3.4	EmVH2.1	Drying of faeces	SPR2.1.3.3, solids collection & storage	SPR2.1.3.4, sum EmV
Output	SPR2.1.3.4	EmV2	Sum emission vitalisation	SPR2.1.3.4, sum EmV	EXPORT
Alternative S3: CaSa					
PR: UDDT					
Input	PR3.1	F3.1	Faeces	IMPORT	SPR3.1.1.2, collection of solids
	PR3.1	U3.1	Urine	IMPORT	SPR3.1.1.1, urine division
	PR3.1	W3.1	Cleansing water	IMPORT	SPR3.1.2, filter
	PR3.1	DM3	Dry material	IMPORT	SPR3.1.1.2, collection of solids
Output	PR3.1	U3.5	Urine after storage in UDDT	SPR3.1.3.2, urine storage	EXPORT
	PR3.1	F3.3	Solids after storage in UDDT	SPR3.1.3.3, solids collection & storage	SPR3.2.1, oven
	PR3.1	EmV3.1	Sum emission volat. UDDT	SPR3.1.3.4, sum EmV	EXPORT
	PR3.1	W3.2	Waste water from cleansing	SPR3.1.2, filter	EXPORT
SPR: toilet					
Input	SPR3.1.1	F3.1	Faeces	IMPORT	SPR3.1.1.2, collection of solids
	SPR3.1.1	U3.1	Urine	IMPORT	SPR3.1.1.1, urine division
	SPR3.1.1	DM3	Dry material	IMPORT	SPR3.1.1.2, collection of solids
Output	SPR3.1.1	F3.2	Solids collected	SPR3.1.1.2, collection of solids	SPR3.1.3.3, solids collection & storage
	SPR3.1.1	U3.2	Urine collected 1	SPR3.1.1.1, urine division	SPR3.1.3.1, urine collection
SPR: urine division					
Input	SPR3.1.1.1	U3.1	Urine	IMPORT	SPR3.1.1.1, urine division
Output	SPR3.1.1.1	U3.3	Urine mixed with solids	SPR3.1.1.1, urine division	SPR3.1.1.2, collection of solids
	SPR3.1.1.1	U3.2	Urine collected 1	SPR3.1.1.1, urine division	SPR3.1.3.1, urine collection
SPR: collection of solids					
Input	SPR3.1.1.2	U3.3	Urine mixed with solids	SPR3.1.1.1, urine division	SPR3.1.1.2, collection of solids
	SPR3.1.1.2	F3.1	Faeces	IMPORT	SPR3.1.1.2, collection of solids
	SPR3.1.1.2	DM3	Dry material	IMPORT	SPR3.1.1.2, collection of solids
Output	SPR3.1.1.2	F3.2	Solids collected	SPR3.1.1.2, collection of solids	SPR3.1.3.3, solids collection & storage
SPR: filter					
Input	SPR3.1.2	W3.1	Cleansing water	IMPORT	SPR3.1.2, filter
Output	SPR3.1.2	W3.2	Waste water from cleansing	SPR3.1.2, filter	EXPORT
SPR: collection & storage					
Input	SPR3.1.3	F3.2	Solids collected	SPR3.1.1.2, collection of solids	SPR3.1.3.3, solids collection & storage
	SPR3.1.3	U3.2	Urine collected 1	SPR3.1.1.1, urine division	SPR3.1.3.1, urine collection
Output	SPR3.1.3	U3.5	Urine after storage in UDDT	SPR3.1.3.2, urine storage	EXPORT
	SPR3.1.3	F3.3	Solids after storage in UDDT	SPR3.1.3.3, solids collection	SPR3.2.1, oven

	Process	Flow	Flow name	Source process	Destination process
				& storage	
	SPR3.1.3	EmV3.1	Sum emission volat. UDDT	SPR3.1.3.4, sum EmV	EXPORT
SPR: urine collection					
Input	SPR3.1.3.1	U3.2	Urine collected 1	SPR3.1.1.1, urine division	SPR3.1.3.1, urine collection
Output	SPR3.1.3.1	EmVN3.1	Gaseous emissions; NH3	SPR3.1.3.1, urine collection	SPR3.1.3.4, sum EmV
	SPR3.1.3.1	U3.4	Urine collected 2	SPR3.1.3.1, urine collection	SPR3.1.3.2, urine storage
SPR: urine storage					
Input	SPR3.1.3.2	U3.4	Urine collected 2	SPR3.1.3.1, urine collection	SPR3.1.3.2, urine storage
Output	SPR3.1.3.2	EmVC3.1	Gaseous emissions; CH4	SPR3.1.3.2, urine storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.2	EmVN3.2	Gaseous emissions; NH3	SPR3.1.3.2, urine storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.2	U3.5	Urine after storage in UDDT	SPR3.1.3.2, urine storage	EXPORT
SPR: solids collection & storage					
Input	SPR3.1.3.3	F3.2	Solids collected	SPR3.1.1.2, collection of solids	SPR3.1.3.3, solids collection & storage
Output	SPR3.1.3.3	EmVC3.2	Gaseous emissions; CH4	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.3	EmVC3.3	Gaseous emissions; CO2	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.3	EmVN3.3	Gaseous emissions; NH3	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.3	EmVH3.1	Drying of faeces	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.3	F3.3	Solids after storage in UDDT	SPR3.1.3.3, solids collection & storage	SPR3.2.1, oven
SPR: sum EmV (UDDT)					
Input	SPR3.1.3.4	EmVN3.1	Gaseous emissions; NH3	SPR3.1.3.1, urine collection	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVC3.1	Gaseous emissions; CH4	SPR3.1.3.2, urine storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVN3.2	Gaseous emissions; NH3	SPR3.1.3.2, urine storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVC3.2	Gaseous emissions; CH4	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVC3.3	Gaseous emissions; CO2	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVN3.3	Gaseous emissions; NH3	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
	SPR3.1.3.4	EmVH3.1	Drying of faeces	SPR3.1.3.3, solids collection & storage	SPR3.1.3.4, sum EmV
Output	SPR3.1.3.4	EmV3.1	Sum emission volat. UDDT	SPR3.1.3.4, sum EmV	EXPORT
PR: sanitation oven					
Input	PR3.2	F3.3	Solids after storage in UDDT	SPR3.1.3.3, solids collection & storage	SPR3.2.1, oven
	PR3.2	Fu3.2	Fuel 2 (firewood)	IMPORT	SPR3.2.2.2, conversion fuel 2
	PR3.2	Fu3.1	Fuel 1 (sawdust)	IMPORT	SPR3.2.2.1, conversion fuel 1
	PR3.2	Ai3	Sum air demand	IMPORT	SPR3.2.5, sum air demand
Output	PR3.2	F3.4	Solids sanitised	SPR3.2.1, oven	EXPORT
	PR3.2	R3	Sum residues	SPR3.2.4, sum residues	EXPORT
	PR3.2	EmV3.2	Sum emission volat. oven	SPR3.2.3, sum EmV	EXPORT
SPR: oven					
Input	SPR3.2.1	F3.3	Solids after storage in UDDT	SPR3.1.3.3, solids collection & storage	SPR3.2.1, oven
Output	SPR3.2.1	EmVH3.2	Evaporated water	SPR3.2.1, oven	SPR3.2.3, sum EmV
	SPR3.2.1	F3.4	Solids sanitised	SPR3.2.1, oven	EXPORT
SPR: gasifier					
Input	SPR3.2.2	Ai3.1	Air demand_fuel 1	SPR3.2.5, sum air demand	SPR3.2.2.1, conversion fuel 1
	SPR3.2.2	Ai3.2	Air demand_fuel 2	SPR3.2.5, sum air demand	SPR3.2.2.2, conversion fuel 2
	SPR3.2.2	Fu3.1	Fuel 1 (sawdust)	IMPORT	SPR3.2.2.1, conversion fuel 1
	SPR3.2.2	Fu3.2	Fuel 2 (firewood)	IMPORT	SPR3.2.2.2, conversion fuel 2
Output	SPR3.2.2	R3.1	Residues 1 (ash&char)	SPR3.2.2.1, conversion fuel 1	SPR3.2.4, sum residues
	SPR3.2.2	R3.2	Residues 2 (ash)	SPR3.2.2.2, conversion fuel 2	SPR3.2.4, sum residues
	SPR3.2.2	EmVFu3.1	Emissions_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.2	EmVFu3.2	Emissions_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV
	SPR3.2.2	Ao3.1	Air out_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.2	Ao3.2	Air out_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV
SPR: conversion fuel 1					
Input	SPR3.2.2.1	Ai3.1	Air demand_fuel 1	SPR3.2.5, sum air demand	SPR3.2.2.1, conversion fuel 1
	SPR3.2.2.1	Fu3.1	Fuel 1 (sawdust)	IMPORT	SPR3.2.2.1, conversion fuel 1
Output	SPR3.2.2.1	EmVFu3.1	Emissions_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.2.1	Ao3.1	Air out_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.2.1	R3.1	Residues 1 (ash&char)	SPR3.2.2.1, conversion fuel 1	SPR3.2.4, sum residues
SPR: conversion fuel 2					
Input	SPR3.2.2.2	Fu3.2	Fuel 2 (firewood)	IMPORT	SPR3.2.2.2, conversion fuel 2
	SPR3.2.2.2	Ai3.2	Air demand_fuel 2	SPR3.2.5, sum air demand	SPR3.2.2.2, conversion fuel 2
Output	SPR3.2.2.2	EmVFu3.2	Emissions_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV

	Process	Flow	Flow name	Source process	Destination process
	SPR3.2.2.2	Ao3.2	Air out_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV
	SPR3.2.2.2	R3.2	Residues 2 (ash)	SPR3.2.2.2, conversion fuel 2	SPR3.2.4, sum residues
SPR: sum EmV (sanitation oven)					
Input	SPR3.2.3	EmVFu3.1	Emissions_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.3	EmVFu3.2	Emissions_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV
	SPR3.2.3	Ao3.1	Air out_fuel 1	SPR3.2.2.1, conversion fuel 1	SPR3.2.3, sum EmV
	SPR3.2.3	Ao3.2	Air out_fuel 2	SPR3.2.2.2, conversion fuel 2	SPR3.2.3, sum EmV
	SPR3.2.3	EmVH3.2	Evaporated water	SPR3.2.1, oven	SPR3.2.3, sum EmV
Output	SPR3.2.3	EmV3.2	Sum emission volat. oven	SPR3.2.3, sum EmV	EXPORT
SPR: sum residues					
Input	SPR3.2.4	R3.1	Residues 1 (ash&char)	SPR3.2.2.1, conversion fuel 1	SPR3.2.4, sum residues
	SPR3.2.4	R3.2	Residues 2 (ash)	SPR3.2.2.2, conversion fuel 2	SPR3.2.4, sum residues
Output	SPR3.2.4	R3	Sum residues	SPR3.2.4, sum residues	EXPORT
SPR: sum air demand					
Input	SPR3.2.5	Ai3	Sum air demand	IMPORT	SPR3.2.5, sum air demand
Output	SPR3.2.5	Ai3.1	Air demand_fuel 1	SPR3.2.5, sum air demand	SPR3.2.2.1, conversion fuel 1
	SPR3.2.5	Ai3.2	Air demand_fuel 2	SPR3.2.5, sum air demand	SPR3.2.2.2, conversion fuel 2
Alternative S4: WC+ST					
PR: water toilet					
Input	PR4.1	F4.1	Faeces	IMPORT	PR4.1, water toilet
	PR4.1	U4.1	Urine	IMPORT	PR4.1, water toilet
	PR4.1	W4.1	Cleansing water	IMPORT	PR4.1, water toilet
	PR4.1	W4.2	Disposal of grey water	IMPORT	PR4.1, water toilet
	PR4.1	W4.3	Flush water	IMPORT	PR4.1, water toilet
Output	PR4.1	SS4.1	Sludge to store	PR4.1, water toilet	SPR4.2.1, septic tank
PR: septic tank					
Input	PR4.2	SS4.1	Sludge to store	PR4.1, water toilet	SPR4.2.1, septic tank
Output	PR4.2	EmV4	Sum emission vitalisation	SPR4.2.2, sum EmV	EXPORT
	PR4.2	EmE4	Sum emission effluent	SPR4.2.3, sum EmE	EXPORT
SPR: septic tank					
Input	SPR4.2.1	SS4.1	Sludge to store	PR4.1, water toilet	SPR4.2.1, septic tank
Output	SPR4.2.1	EmVC4.1	Gaseous emissions; CH4	SPR4.2.1, septic tank	SPR4.2.2, sum EmV
	SPR4.2.1	EmVC4.2	Gaseous emissions; CO2	SPR4.2.1, septic tank	SPR4.2.2, sum EmV
	SPR4.2.1	EmEP4	Liquid emissions; PO43-	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
	SPR4.2.1	EmEN4	Liquid emissions; NH4+	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
	SPR4.2.1	EmEH4	Effluent; H2O	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
SPR: sum EmE					
Input	SPR4.2.1	EmEP4	Liquid emissions; PO43-	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
	SPR4.2.3	EmEN4	Liquid emissions; NH4+	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
	SPR4.2.3	EmEH4	Effluent; H2O	SPR4.2.1, septic tank	SPR4.2.3, sum EmE
Output	SPR4.2.3	EmE4	Sum emission effluent	SPR4.2.3, sum EmE	EXPORT
SPR: sum EmV					
Input	SPR4.2.2	EmVC4.1	Gaseous emissions; CH4	SPR4.2.1, septic tank	SPR4.2.2, sum EmV
	SPR4.2.2	EmVC4.2	Gaseous emissions; CO2	SPR4.2.1, septic tank	SPR4.2.2, sum EmV
Output	SPR4.2.2	EmV4	Sum emission vitalisation	SPR4.2.2, sum EmV	EXPORT

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B.8. LIST OF ABBREVIATIONS

The list of abbreviations refers to the abbreviations used in the text. The abbreviations used to designate the parameters are not included here but have always been explained when the respective equation was introduced.

AES	Agroecosystem
AirIn	Input of air
AirOut	Output of air
Att	Attitude
BOD	Biochemical oxygen demand
C	Carbon
CaSa	Carbonization and Sanitation
c	concentrations
calc.	Calculated values
DM	Dry matter
DMT	Dry material
EcoSan	Ecological sanitation
EF	Emission factor
EmE	Emissions from effluents
EmV	Emissions from volatilisation
EP	Eutrophication potentials
FM	Fresh matter
FR	Fuel requirement
frac	Mass fraction
G	Goods
GHG	Greenhouse gas
GWP	Global warming potentials
hh	households
IPCC	Intergovernmental Panel on Climate Change
$\dot{m}$	Material flow
MCF	Methane correction factor
MF	Model factor
MFA	Material flow analyses
MSS	Micro sanitation system
n	Total sample size, i.e. number of replications
N	Nitrogen
NA	Not analysed
NGO	Non-governmental organisation
OM	Organic matter
P	Phosphorus
σ	Standard deviation
ρ	Density
Res	Residues
RU	Relative uncertainty
UCR	Urine collection rate
UDDT	Urine-diverting dry toilet
STAN	subSTance flow ANalysis
TC	Transfer coefficients
TZ	Tanzania
TU	Technische Universität
TZS	Tanzanian shilling
WHO	World Health Organization
$\bar{x}$	Mean value
Δx	Standard error

A3: Appendix to P5 - Multi-Criteria Technology Assessment

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APPENDIX OF

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

A. Krause, J. Köppel
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

TABLE OF CONTENT

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 • Decision for inviting representatives of all partners of the case study projects to participate.	Commitment to participate throughout the whole MCTA-process.	Mar. 2015
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:* Preparing final presentation for sharing results of MCTA with all participants.	8. *Conclusion*: Reading presentation.	Oct. 2016
	9. *Evaluation:* Preparing questionnaire for feedback; evaluating and visualizing evaluation.	9. *Evaluation*: Answering questionnaire to provide feedback and criticism, and to formulate lessons learned.	Nov. 2016

(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.

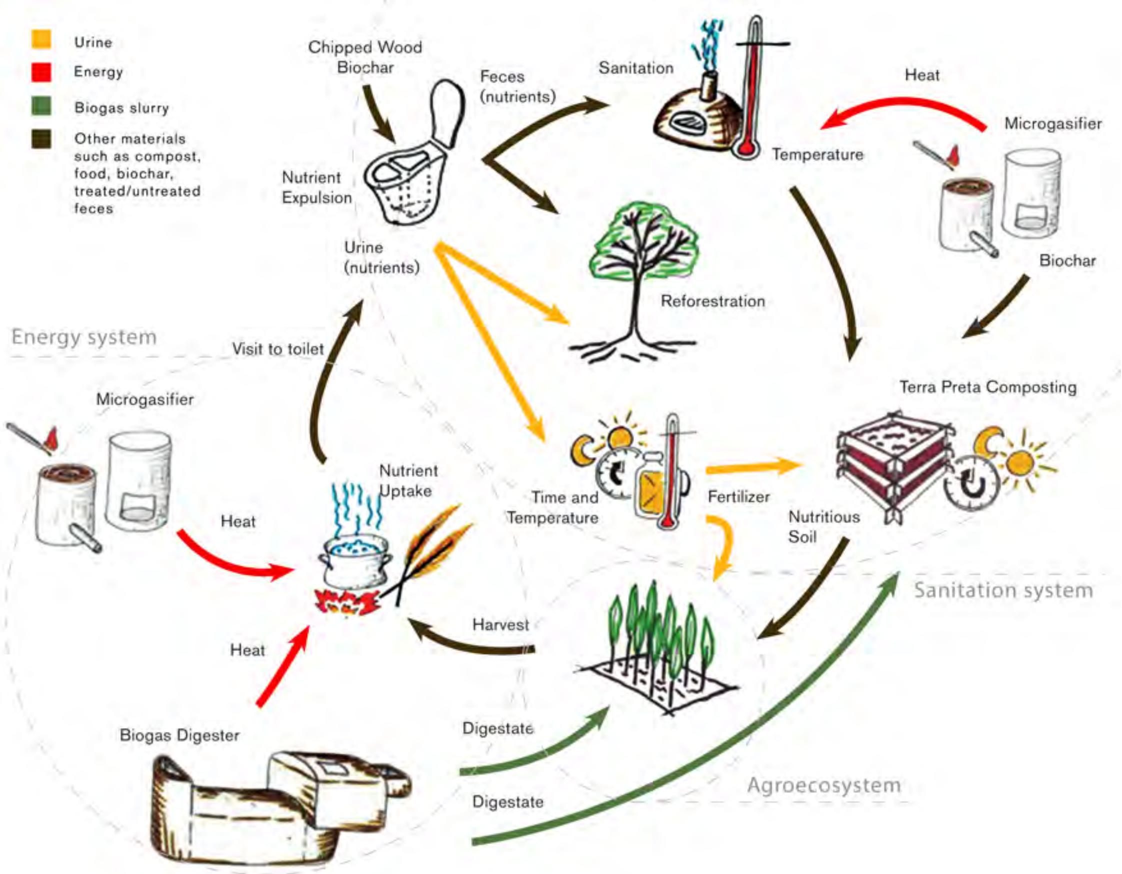


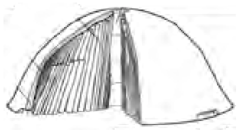
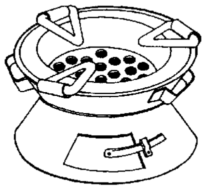
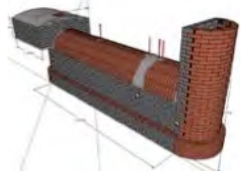
Fig. A.1: Pictorial illustration of the intersectional resource management in smallholder farming systems integrates also cooking and sanitation technologies assessed through MCTA (Krause et al., 2015)

(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).

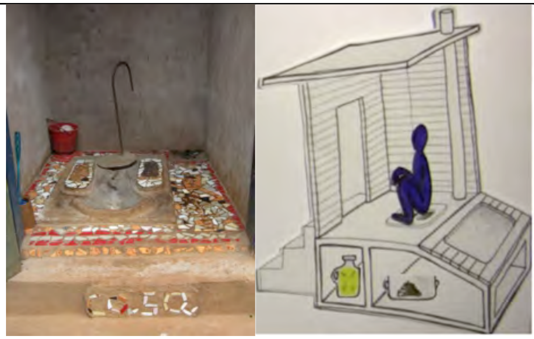
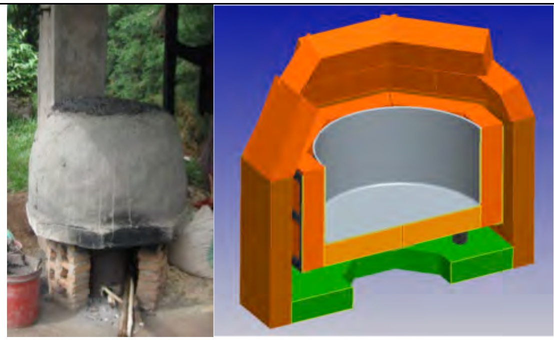
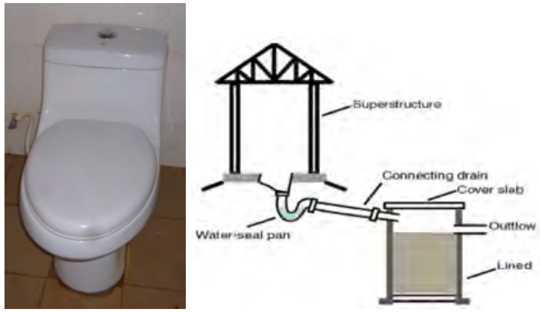
We also discussed options to compare different scenarios representing different strategies for sustainable community development in Karagwe with staff members of MAVUNO and CHEMA and decided on the following concept: The first scenario is a current state scenario; the second scenario describes a switch 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	
						
						
						1-combuster, 2-pot stand
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.	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)

EcoSan UDDT only	CaSa UDDT and sanitation oven	WC + ST Water toilet (Closet) and Septic Tank
		
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.		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.
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*.	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].	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.

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.

Interviews 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.

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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,

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.

Critique: 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.

Step 5:

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.

Step 6:

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. CO2, CH4, N2O, 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 (NH4, PO4) 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)	

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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

A4: Appendix to Section 7.2.1 of the main text of the thesis '*Valuing Wastes*'

APPENDIX OF

Section 7.2.1

CONSUMPTIVE AND PRODUCTIVE USES OF SUBSTRATES ANALYSED FOR USE IN FOOD PRODUCTION

A. Krause
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

A5.1. Basic assumptions and simplification

- Agriculture is rain-fed only, no irrigation is applied.
- No synthetic fertilizers are used as smallholder organic farming is practiced.
- No animal manure is used as the analysis refers to structurally poor households.
- The total farmland consists of *shamba* and *msiri*.
  - *Shamba*: banana-based homegardens intercropped with beans, coffee, tomato and eggplant, etc.
  - *Msiri*: former grassland used for cultivation of annual crops like maize, beans, etc.; including a part for vegetable production called 'kitchen garden'.

A5.2. Size of available land

- Shamba:
  - Total size: 0.5 ha = 5,000 m^2.
  - Used for intercropping of perennial and annual crops as cover crops.
  - → Cultivation of banana and beans.
- Msiri
  - Total size: 0.125 ha = 1,250 m^2.
  - Used for intercropping of annual crops.
  - → Cultivation of maize, beans, cabbage, and onion.

A5.3. Estimating the food production

The annual harvest of a specific crop i is estimated as the product of the annual yields assumed for the specific crop and the size of land that is planted with the respective crop. Yield assumptions for the crops grown on the *msiri* are based on literature data combined with empiric data from the field experiment. The quantification of crop production is part of the SNB (see Appendix A3 to P4). Yield assumptions for the *shamba* are based only on literature data. The assumed crop yields vary depending on the different scenarios analysed. The yield assumptions (Y_i and y_i) of the crops are presented in Tables A5.5- A5.11 at the end of the present appendix.

$H_i = Y_i \cdot A_i$ Eq. A5.1

with $Y_i = y_i \cdot S_i$ Eq. A5.2

and $A_i = A_X \cdot a_i$ Eq. A5.3

With:

H_i:	Total *annual* harvest of a crop i [kg hh^{-1} yr^{-1}] with i = {banana, maize, beans, onion, cabbage}
Y_i:	Assumed *annual* yield of a crop i [t ha^{-1} yr^{-1}]
A_i:	Area of land planted with a crop i [ha^{-1} yr^{-1}]
y_i:	Assumed *seasonal* yield of a crop i [t ha^{-1} season^{-1}]
S_i:	Number of season that a crop i is cultivated per year [season yr^{-1}]
a_i:	Share of land planted with a crop i [%]
A_x:	Total size of planted land X with X = {shamba, msiri}

The total food production is then determined through aggregation of specific crops contributing to feed the household members with staple food, pulses, and vegetables.

$$H_{staple\,food} = H_{banana} + H_{maize}$$ Eq. A5.4

$$H_{pulses} = H_{beans}$$ Eq. A5.5

$$H_{vegetables} = H_{cabbage} + H_{onion}$$ Eq. A5.6

A5.4. Allocation of harvest products

The total food production is allocated to 'own consumption' and 'income generation' through, respectively:

$$H_{consumptive,i} = H_i \cdot s_{concumptive,i}$$ Eq. A5.7

$$H_{productive,i} = H_i \cdot s_{productive,i}$$ Eq. A5.8

With:

H_i: Total *annual* harvest of a crop i [kg hh^{-1} yr^{-1}]

$H_{consumptive,i}$: Total *annual* harvest of a crop i, which was used for own consumption in the smallholder household [kg hh^{-1} yr^{-1}]

$H_{productive,i}$: Total *annual* harvest of a crop i, which was used for productive purposes, i.e. sold on local markets or to intermediaries for generating income [kg hh^{-1} yr^{-1}]

$s_{concumptive,i}$: Share of the harvest used for own consumption [% of H_i]

$s_{productive,i}$: Share of the harvest used for income generation [% of H_i]

The shares that indicate to which percentage of the total harvest a particular crop i is used for own consumption ($s_{concumptive,i}$) or for income generation ($s_{productive,i}$) are presented in Table A5.2. The remainder of the harvest is sold on local markets and to intermediaries ($s_{productive,i}$) (Eq. A5.9).

$$s_{productive,i} = 100\ \% - s_{concumptive,i}$$ Eq. A5.9

Table A5.2: Basic assumptions of the modelling

	Share of land planted with the respective crop (= a_i)	Size of land planted with the respective crop (= A_i)		Share of the harvest used for own consumption (as common)	Share of the harvest used for selling (as common)
		m^2 hh^{-1} yr^{-1}	m^2 cap^{-1} yr^{-1}	($s_{concumptive,i}$)	($s_{productive,i}$)
Shamba					
Banana	100 %	5000	833	56 %	44 %
Beans	50 %	1500	250	38 %	62 %
Msiri					
Maize	80 %	1000	167	66 %	34 %
Beans	15 %	188	31	38 %	62 %
Onion	2.5 %	31	5	100 %	0 %
Cabbage	2.5 %	31	5	100 %	0 %

The average shares, as typical for farmers of MAVUNO, were quantified via questionnaire during pre-studies of this work conducted by A. Krause and I. Bamuhiga in 2010. During the analysis, the shares have been adapted to make sure that sufficient but not exceeding food is available to the household members. Thus, the shares of the harvest used for own consumption were increased if the initially allocated share of the production did not meet the need for food. Accordingly, the shares used for own consumption were decreased if the initially allocated share of the production exceeded the need for food. The adapted shares are presented in Table A5.3.

Table A5.3: Share of the harvest used for "own consumption" ($s_{concumptive,i}$).

	Share of the harvest used for own consumption (as common)	Share of the harvest used for own consumption (adopted) A1	Share of the harvest used for own consumption (adopted) A2	Share of the harvest used for own consumption (adopted) A3	Share of the harvest used for own consumption (adopted) A4
Shamba					
Banana	56 %	**100 %**	NA	NA	NA
Beans	38 %	**59 %**	**42 %**	**20 %**	**25 %**
Msiri					
Maize	66 %	**100 %**	66 %	**43 %**	**59 %**
Beans	38 %	**59 %**	**42 %**	**20 %**	**25 %**
Onion	100 %	100 %	100 %	100 %	100 %
Cabbage	100 %	100 %	100 %	100 %	100 %

Adapted values compared to the current state are indicated in **bold**. NA: not analysed.

A5.5. Food demand

The basic nutritional needs of smallholders are estimated on the basis of a literature review (Table A5.4). Therefore, it was assumed that one smallholder household (hh) comprises on average six household members (Tanzania, 2012).

Table A5.4: Summary of data collected from literature regarding the basic nutritional needs of human beings

	g cap^{-1} d^{-1}	kg cap^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	Comment	Source
Maize, rice, bulgur	400	146	876	Food requirements in emergency situations	PAHO, n.d.; UNHCR, 2002
Legumes	60	22	131		
	m^{2} cap^{-1} yr^{-1}	kg cap^{-1} yr^{-1}	kg hh^{-1} yr^{-1}		
Vegetables (incl. potatoes)	51.5	124	744	Food production in Germany, for comparison with a food-secure country	BMELV, 2009
Potatoes	32.4	65	390		
Vegetables (incl. 26 species)	19.1	59	354		
Maize, cereals	295	114	684		

A5.6. Producer prices

Local producer prices are:

- 400 TZS kg^{-1} for maize.
- 720 TZS kg^{-1} for beans.

These prices are determined from the mean prices in TZS bucket^{-1} (*debe*), which local farmers receive when selling to an intermediary. Mean prices have been provided by Mavuno (2014) alongside the per-bucket-weight for maize and beans, which are 17 kg debe^{-1} and 20 kg debe^{-1}, respectively.

A5.7. Tables summarizing the yield assumptions and harvest results for the different crops analysed

Table A5.5: Yield assumptions and harvest results for banana and the four scenarios analysed (A1-A4)

Banana	Yield assumption t ha^{-1} yr^{-1}	t ha^{-1} season^{-1}	based on	Consumptive kg hh^{-1} yr^{-1}	Productive kg hh^{-1} yr^{-1}	Total harvest kg hh^{-1} yr^{-1}
A1	1.0		Average TZ*	268	215	482
A2	1.6		'Base value' Tanzania (2012)	444	356	800
A3	3.9		'Base value' Mavuno (2014)	444	356	800
A4	1.6		'Base value' Tanzania (2012)	444	356	800

* The average for Tanzania (TZ) is determined from literature (Baijukya et al., 1998; FAOSTAT, 2012a; Mavuno, 2014; Smaling et al., 1993; Tanzania, 2012).

Table A5.6: Yield assumptions and harvest results for maize and the four scenarios analysed (A1-A4)

Maize	Yield assumption t ha^{-1} yr^{-1}	t ha^{-1} season^{-1}	based on	Consumptive kg hh^{-1} yr^{-1}	Productive kg hh^{-1} yr^{-1}	Total harvest kg hh^{-1} yr^{-1}
A1	2.4	1.2	Average TZ without fertilizer*	159	84	243
A2	5.3	2.6	Biogas slurry (P2)	344	181	525
A3	8.8	4.4	CaSa-compost (P2)	574	303	877
A4	6.4	3.2	Standard compost (P2)	417	219	636

* The average for TZ is determined from literature (FAOSTAT, 2012b; Krause et al., 2016; Smaling et al., 1993; Tanzania, 2012); 'P2' refers to the second publication of the present dissertation (Krause et al., 2016).

Table A5.7: Yield assumptions and harvest results for beans and the four scenarios analysed (A1-A4)

Beans	Yield assumption $t\ ha^{-1}\ yr^{-1}$	$t\ ha^{-1}\ season^{-1}$	based on	Consumptive $kg\ hh^{-1}\ yr^{-1}$	Productive $kg\ hh^{-1}\ yr^{-1}$	Total harvest $kg\ hh^{-1}\ yr^{-1}$
A1	1.3	0.7	Average TZ without fertilizer*	85	138	223
A2	1.9	0.9	Biogas slurry (P2)	120	196	316
A3	9.8	4.9	CaSa-compost (P2)	251	410	661
A4	3.2	1.6	Standard compost (P2)	204	333	536

* The average for TZ is determined from literature (Baijukya et al., 1998; Krause et al., 2016; Mavuno, 2014; Smaling et al., 1993; Tanzania, 2012); 'P2' refers to the second publication of the present dissertation (Krause et al., 2016).

Table A5.8: Yield assumptions and harvest results for beans (from *shamba* only) and the four scenarios analysed (A1-A4)

Beans *shamba*	Yield assumption $t\ ha^{-1}\ yr^{-1}$	$t\ ha^{-1}\ season^{-1}$	based on	Consumptive $kg\ hh^{-1}\ yr^{-1}$	Productive $kg\ hh^{-1}\ yr^{-1}$	Total harvest $kg\ hh^{-1}\ yr^{-1}$
A1	1.3	0.7	Average TZ without fertilizer*	75	123	198
A2	1.9	0.9	Biogas slurry (P2)	107	174	281
A3	9.8	4.9	CaSa-compost (P2)	181	296	477
A4	3.2	1.6	Standard compost (P2)	181	296	477

* see Table A5.7.

Table A5.9: Yield assumptions and harvest results for beans (from *msiri* only) and the four scenarios analysed (A1-A4)

Beans *msiri*	Yield assumption $t\ ha^{-1}\ yr^{-1}$	$t\ ha^{-1}\ season^{-1}$	based on	Consumptive $kg\ hh^{-1}\ yr^{-1}$	Productive $kg\ hh^{-1}\ yr^{-1}$	Total harvest $kg\ hh^{-1}\ yr^{-1}$
A1	1.3	0.7	Average TZ without fertilizer*	9	15	25
A2	1.9	0.9	Biogas slurry (P2)	13	22	35
A3	9.8	4.9	CaSa-compost (P2)	70	114	184
A4	3.2	1.6	Standard compost (P2)	23	37	60

* see Table A5.7.

Table A5.10: Yield assumptions and harvest results for onion and the four scenarios analysed (A1-A4)

Onion	Yield assumption $t\ ha^{-1}\ yr^{-1}$	$t\ ha^{-1}\ season^{-1}$	based on	Consumptive $kg\ hh^{-1}\ yr^{-1}$	Productive $kg\ hh^{-1}\ yr^{-1}$	Total harvest $kg\ hh^{-1}\ yr^{-1}$
A1	7.8	3.9	Average TZ without fertilizer*	24	0	24
A2	28.4	14.2	Standard compost (P2)	88	0	88
A3	28.4	14.2	Standard compost (P2)	88	0	88
A4	28.4	14.2	Standard compost (P2)	88	0	88

* The average for TZ is determined from literature (Krause et al., 2016; Tanzania, 2012); 'P2' refers to the second publication of the present dissertation (Krause et al., 2016).

Table A5.11: Yield assumptions and harvest results for cabbage and the four scenarios analysed (A1-A4)

Cabbage	Yield assumption $t\ ha^{-1}\ yr^{-1}$	$t\ ha^{-1}\ season^{-1}$	based on	Consumptive $kg\ hh^{-1}\ yr^{-1}$	Productive $kg\ hh^{-1}\ yr^{-1}$	Total harvest $kg\ hh^{-1}\ yr^{-1}$
A1	83.2	41.6	Standard compost (P2)	258	0	258
A2	83.2	41.6	Standard compost (P2)	258	0	258
A3	83.2	41.6	Standard compost (P2)	258	0	258
A4	83.2	41.6	Standard compost (P2)	258	0	258

* see Table A5.10.

A5: Appendix to Section 7.2.2 of the main text of the thesis '*Valuing Wastes*'

APPENDIX OF

Section 7.2.2

LONG-TERM EFFECTS OF THE RECYCLING PRACTICES STUDIED ON CROP YIELDS AND SOIL NUTRIENTS

A. Krause
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

A6.1. Description of the SWIM-model

The Soil and Water Integrated Model (SWIM), a process-based, eco-hydrological model, was developed by the Potsdam Institute for Climate Impact Research (PIK). According to Krysanova et al. (2000), the SWIM integrates hydrology, erosion, vegetation, as well as nitrogen (N) and phosphorus (P) dynamics at the river basin scale (Fig. A6.1). The model further uses climate input data and agricultural management data as external forcing. Altogether, the SWIM comprises the following parts:

1. The **model of crop and natural vegetation** can simulate a wide range of arable crops (e.g. wheat, barley, corn, potatoes, alfalfa, etc.). SWIM uses unique parameter values for each crop, which were obtained in different field studies. The crop-and-vegetation-model is an important interface between hydrology and nutrients (Fig. A6.2). Relevant processes and flows in the model are described in more detail below.
2. The **nutrient modules** include models of the N- and P-cycle (Figs. A6.3-A6.5).
3. The **hydrological model** includes the soil surface, the root zone, the shallow aquifer, and the deep aquifer. The soil column is subdivided into several layers in accordance with the soil database. The water balance for the soil column includes precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff.
4. Information about the **climate, land use patterns, and land management** (i.e. 'the way of farming') are usually provided as input data by the SWIM-users or transferred from databases (for site-specific climate data).

The structure and computations of the crop and nutrient models[1] are further described in the following sections. Thereafter, the input data used to describe the land management is briefly summarized and followed by a brief description of the evaluation applied on output data.

(1) Crop model

According to the SWIM-Manual (Krysanova et al., 2000), the applied model to simulate crop yields is a simplification of the EPIC crop model of Williams et al. (1984). All processes that are considered in SWIM are described in detail in Sections 2.2.1–2.2.5 in Krysanova et al. (2000) and are summarized in Fig. A6.1. Overall, the **crop model in SWIM** considers:

a) Phenological development of the crop;
b) Potential increase in biomass for a day;
c) Actual daily increase in biomass;
d) Plant stress factors;
e) Partitioning grain yields.

[1] The computational modeling, including equations, is described in detail in the SWIM-manual on pp. 34-94 (Krysanova et al., 2000). A List of

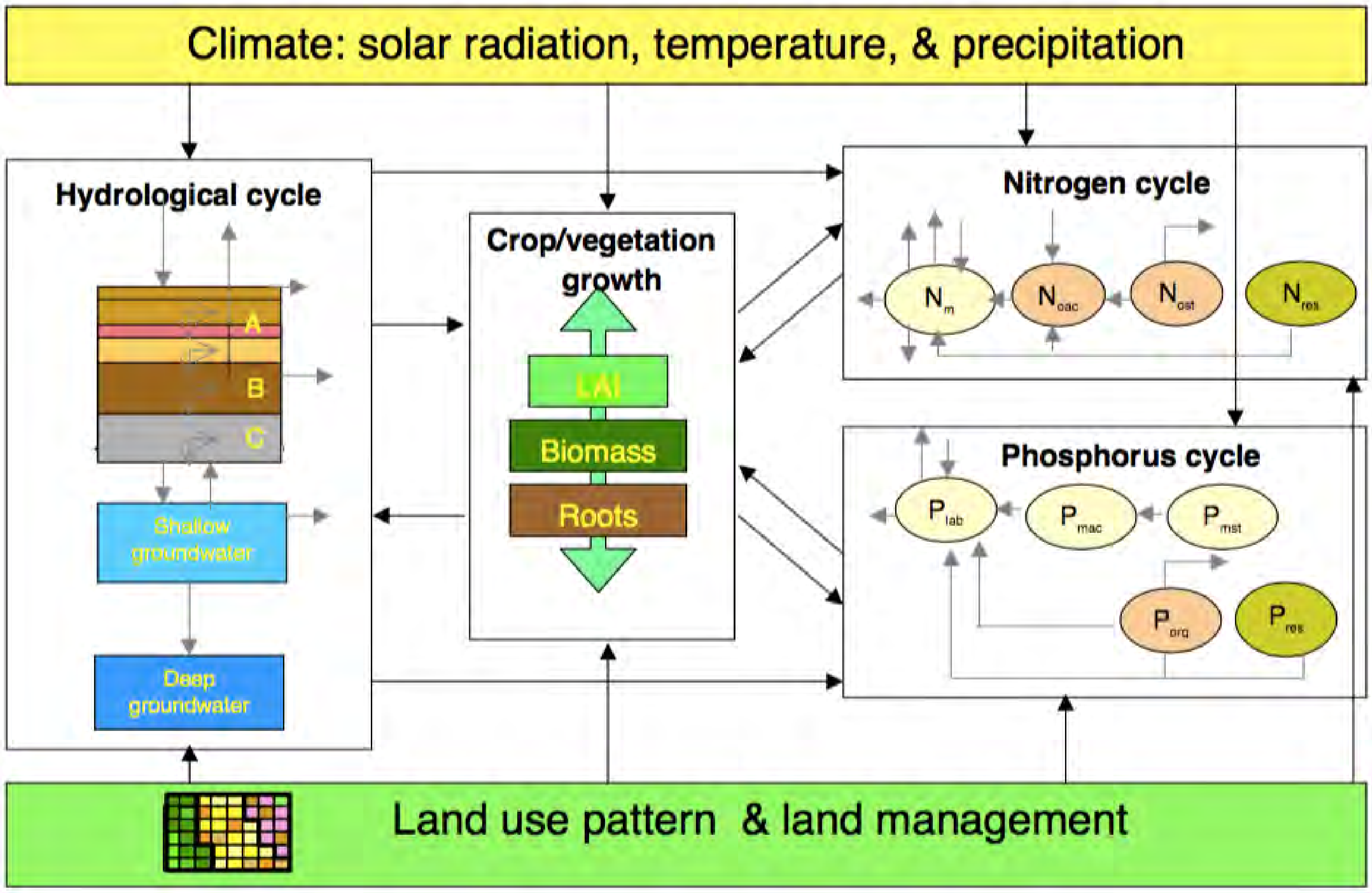

Fig. A6.1: Flow chart of the SWIM model, integrating hydrological processes, crop/vegetation growth, and nutrient dynamics (from Krysanova et al., 2000).

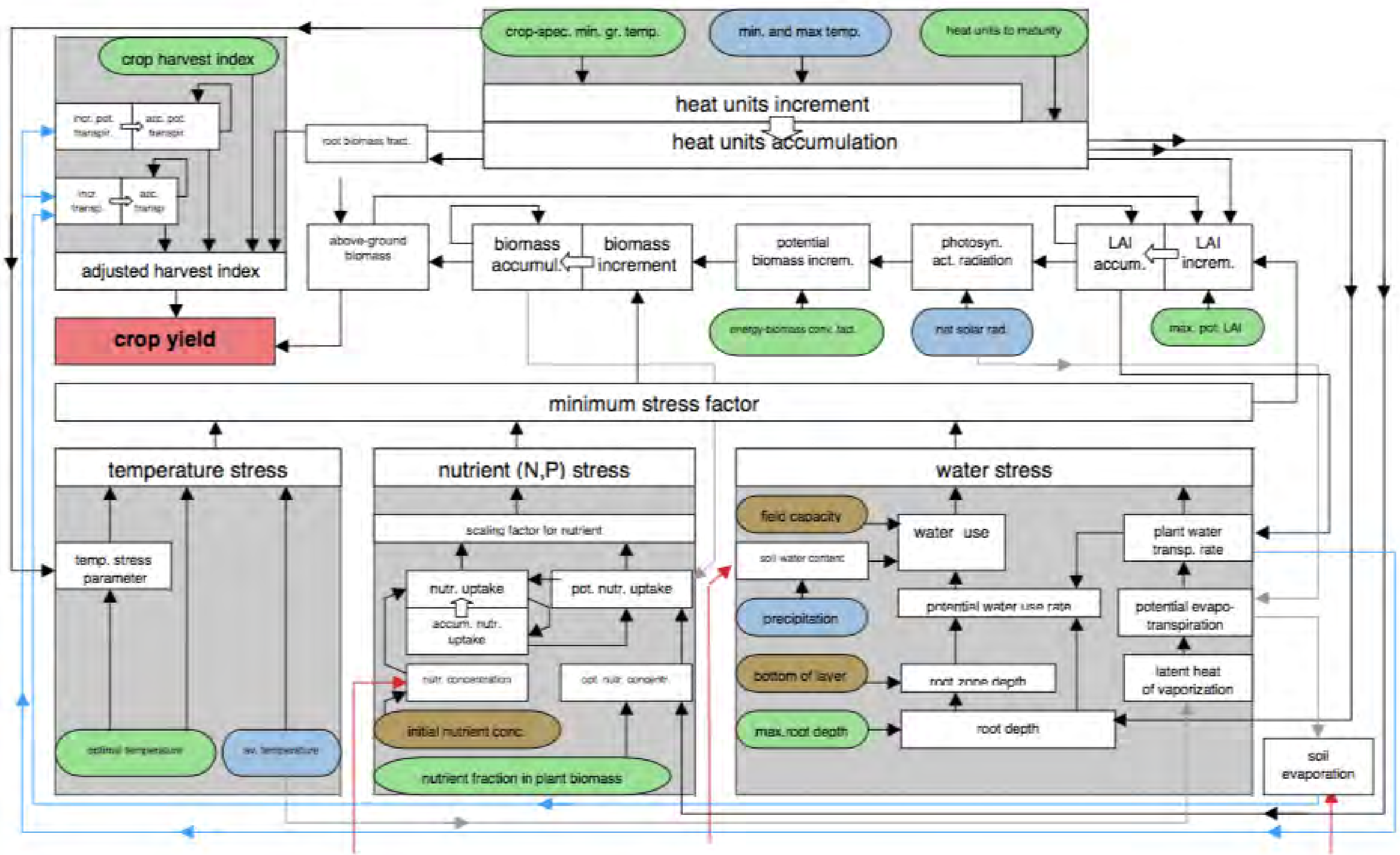

Fig. A6.2: Scheme of operations included in SWIM crop module (from Krysanova et al., 2000).
The grey coloured boxes indicate the three basic blocks in the crop module; the small rectangles denote dependent variables, whereas the coloured ovals refer to model parameters independent from the others computed within the module (including specifications of crop in green, climate in blue, and soil in brown

(1a) The phenological development of the crop:

The phenological development of the crop is based on the accumulation of daily heat units (HUNA), which is put in relation to the value of potential heat units required for the maturity of the crop (PHUN). The $\sum HUNA\ (t)$ is estimated from the crop specific minimum growth temperature, the daily minimum and maximum air temperatures, and the assumed accumulated heat units.

Then, the ratio (quotient) of $\frac{\sum HUNA\ (t)}{PHUN}$ is compared to the heat unit index (IHUN), which ranged from 0 at planting to 1 at physiological maturity of the crop (Eqs. 81-83 in Krysanova et al., 2000).

(1b) The potential increase in biomass for a day:

The potential increase in biomass for a day is calculated pursuant to the approach of Monteith (1977) whereby the daily potential increase in total biomass (ΔBP) is the product of a crop-specific parameter for converting energy to biomass (BE) and the photosynthetic active radiation (PAR), which depends on the solar radiation and the leaf area index (Eq. 84 in Krysanova et al., 2000).

(1c) The actual daily increase in biomass:

The potential increase in biomass is adjusted daily if one of the plant stress factors is less than 1.0. The estimated daily biomass growth is the product of a minimum stress factor and the potential biomass (Eq. 85 in Krysanova et al., 2000).

(1d) The plant stress factors:

SWIM considers four factors that stress plants and plant growth:

- The water stress (WS) factor is defined as the ratio of actual to potential plant transpiration.
- The temperature stress (TS) factor is computed as a function of daily average temperature, optimal and base temperatures for plant growth.
- The nutrient stress factors, including nitrogen stress (NS) and phosphorus stress (PS).

The nutrient stress factors are based on '*the ratio of simulated plant N and P contents to the optimal values of nutrient content*'. The stress factors vary non-linearly:

- the factor is 0 when the actual nutrient uptake of N or P is half of the potential nutrient uptake (i.e. the optimal level of nutrient uptake for plants), for example: $if\ \frac{N_{uptake}}{N_{optimal}} = 0.5\ then\ NS = 0$
- the factor is 1 when the actual nutrient uptake of N or P is equivalent to the potential nutrient uptake, for example: $if\ \frac{N_{uptake}}{N_{optimal}} = 1.0\ then\ NS = 1$

The crop growth regulating factor (REGF) is estimated as the minimum of these four factors (Eq. 86 in Krysanova et al., 2000).

(1e) Partitioning grain yields.

SWIM calculates the crop yield (YLD) by using the harvest index concept. The YLD is the product of the above-ground biomass (BAD) and the harvest index (HI). The HI is a function of IHUN and is often a relatively stable value across a range of environmental conditions. Harvest index increases non-linearly during the growth season (estimated as the function of HUNA) so that most of the economic yield is gained in the second half of the growing season. The BAG and YLD are indicated in kg ha^{-1} (Eqs. 102-103 in Krysanova et al., 2000). Furthermore, '*most crops are particularly sensitive to water stress, especially in the second half of the growing season, when major yield components are determined*' (Krysanova et al., 2000, p. 62).

(2) Nutrient models

Alongside the crop model, SWIM also contains a N- and P-model depicting the nutrient dynamics and nutrient flows in the soil (Fig. A6.3). Mineralisation, decomposition, and soil erosion are the main processes that control the nutrient pools in the SWIM-based simulation of nutrient dynamics (Sections 2.3.1-2.3.9 in Krysanova et al., 2000). Mineralisation is influenced by soil temperature, soil water content, field capacity and the humus rate constant. The decomposition rate essentially depends on the C-N-ratio, C-P-ratio and soil temperature. The wash-off to surface water and leaching to groundwater are more important for N, while P is mainly transported with erosion.

The **N-module** in SWIM (Fig. A6.4) operates with four main pools, namely:

1. nitrate (ano3),
2. stable organic N (anors),
3. mineralisable organic N (anora), and
4. fresh organic N from crop residue (fon).

The N-module further contains the flows: fertilisation, input with precipitation, mineralisation, denitrification, plant uptake, wash-off with surface and subsurface flows, leaching to ground water, and loss with erosion.

The **P-module** in SWIM (Fig. A6.5) operates with five main pools, namely:

1. labile P (plab),
2. organic P (porg),
3. active mineral P (pma),
4. stable mineral P (pms), and
5. fresh organic P from crop residue (fop).

The P-module further contains the flows: fertilisation, sorption/desorption, mineralisation, plant uptake, loss with erosion, wash-off with lateral flow.

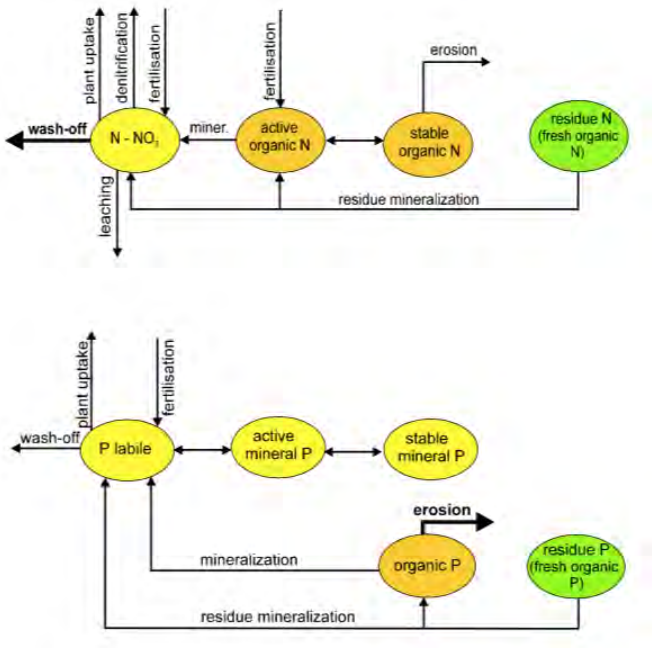

Fig. A6.3: Nitrogen and phosphorus flow-charts as implemented in SWIM (from Krysanova et al., 2000).

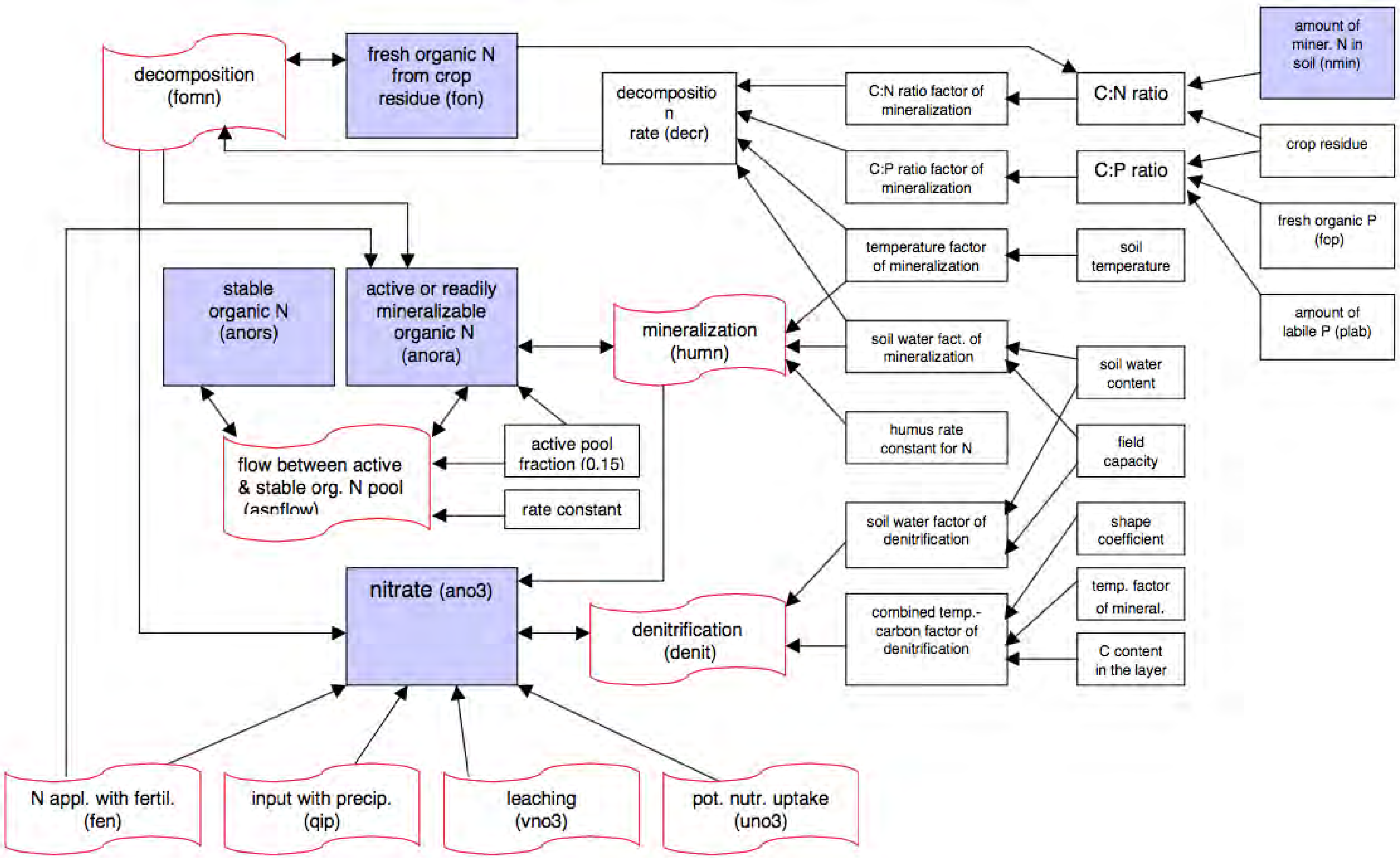

Fig. A6.4: Scheme of operations included in SWIM N-module (from Krysanova et al., 2000).
The blue rectangles indicate the four main N-pools depicted in SWIM; flags indicate flows that influence the nitrate pool; rectangles represent other variables and parameters.

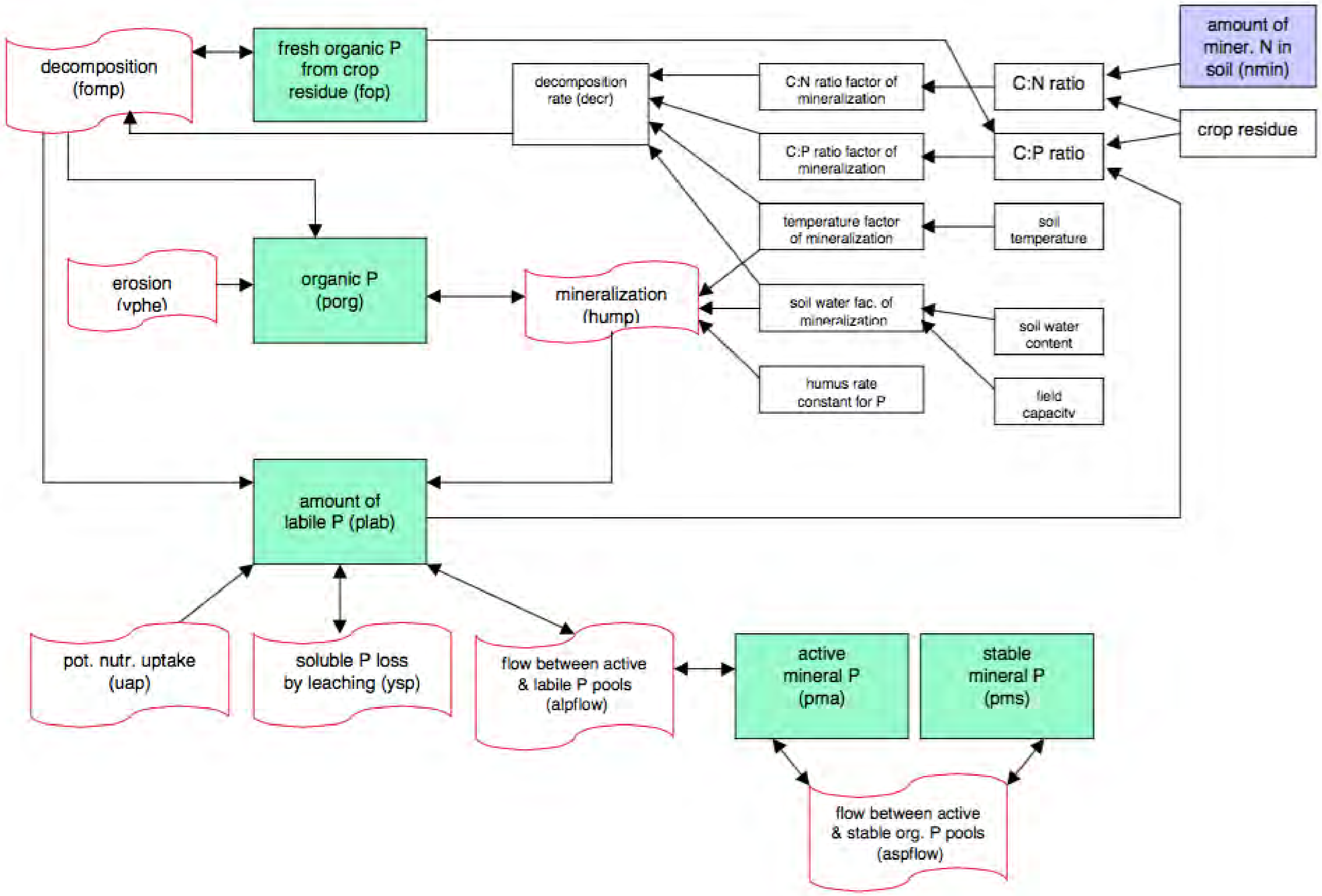

Fig. A6.5: Scheme of operations included in SWIM N-module (from Krysanova et al., 2000).
The green rectangles indicate the five main P-pools depicted in SWIM; flags indicate flows that influence the pool of labile P and two-directional exchange flows between active and stable mineral P, and the mineralisation and decomposition flows; rectangles represent other variables and parameters.

A6.2. Model calibration

For the **initial calibration**, which we carried out before starting the modelling, we **adjusted SWIM to the specific regional conditions**. For this, we used data on soil and climate characteristics that were collected during an exploratory study conducted in Karagwe in 2014. The input data used for characterising and depicting the local soil in SWIM is summarized in Table A6.1. The data used for characterising the local climate (rainfall and humidity) is presented in the Supplements to P2 of the dissertation (Supplements of Krause et al., 2016). Comments regarding the **profiling of the local soil** in Karagwe:

- Soil name: Andosol
- Layers: 4 resp. 5
- Arable layers: 3
- Number of soil profiles: 2
- Names of soil horizons: Ap Ah B C (with more than 90 % stones and gravel in C)
- Porosity and available water capacity were only determined for the soil layer 0-30 cm.
- Saturated conductivity (mm/h) was determined with double-ring infiltration experiment in the field.
- Content of total carbon (C_{tot}) and total nitrogen (N_{tot}) was analysed for soil layers 0-30, 30-60 and 60-90 cm.
- Erosion or erodibility factor (Kw, Kf) were unanalysed (ua.) for both soil profiles.

Table A6.1: Input data of soil profiles

		Soil profile no. 1					Soil profile no. 2			
Horizon		1	2	3	4	5	1	2	3	4
Depth	mm	200	370	530	740	1000	150	300	650	1000
Clay content	%	3.2	3.6	2.2	2.2	ua.	1.8	2.4	1.5	ua.
Silt content	%	16.1	13	16.3	20.1	ua.	17.1	17.9	23.8	ua.
Sand content	%	80.7	83.4	81.5	77.8	ua.	81.2	79.8	74.8	ua.
Bulk density	g cm^{-3}	0.94	0.88	1.08	ua.	ua.	ua.	ua.	ua.	ua.
Porosity	%	59.3	59.3	ua.	ua.	ua.	59.3	59.3	ua.	ua.
Available water capacity		12.9	12.9	ua.	ua.	ua.	12.9	12.9	ua.	ua.
Field capacity	%	27.5	27.5	26.5	20.7	ua.	27.5	27.5	26.5	20.7
C_{tot} content	%	3.5	3.5	2.7	2	ua.	3.5	3.5	2.7	2
N_{tot} content	%	0.28	0.28	0.2	0.16	ua.	0.28	0.28	0.2	0.16
Saturated conductivity	mm h^{-1}	253	253	253	253	253	253	253	253	253

Hence, data of two soil profiles were available, which we used as input to SWIM *separately*. This means, that during modelling, SWIM runs two times, for each of the soil profiles. Then, the average value of a certain output parameter is determined as the mean of the respective results for each of the two soil profiles.

Based on a first test, the **model was again calibrated and further adjusted**. Therefore, we compared the maize grain yields estimated by SWIM with the results gained in the field experiment conducted in Karagwe in 2014. We found that SWIM initially overestimated the grain yields. According to C. Gornott, with whom I cooperated at the PIK and who essentially helped me in conducting the analysis, SWIM is not yet sufficiently adopted to rain-fed agriculture in semi-arid and tropical regions like Karagwe. Nonetheless, SWIM has already been adjusted with respect to modelling the crop-available moisture in the soil (for depicting water stress) by adopting *the classical Mitscherlich equation* pursuant to Harmsen (2000). We further adapted the model to regional conditions as typical for sub-Saharan Africa by adjusting the harvest index according to Folberth et al. (2012). However, in particular the distribution of N_{min} and N_{org} applied to the several N-pools in the soil still needs improvements and further effort in developing the model. Hence, we reacted on this limitation by adjusting the input data and assuming that 20 % of the N_{org} applied with the analysed fertilizers are directly/immediately allocated to N_{min}. The latter was done to reflect the fast mineralisation processes taking place under local tropical conditions with elevated temperatures and because cultivation is done during the rainy season, thus under very humid conditions. We further adopted the model regarding the P-fixation depicted by setting the respective model parameter to be 80 % of the total P applied to reflect the local Andosol in Karagwe.

A6.3. Input data

Before starting the SWIM-analysis, the underlying **basic assumptions and simplification with respect to the cropping system analysed** were defined as:

- Agriculture is **rain-fed only**, no irrigation is applied.
- No synthetic fertilizers are used as smallholder *organic* farming is practiced.
- No animal manure is used as analysis refers to structurally poor households (and vegan organic farming).
- Total farmland of smallholders in Karagwe consists of *shamba* and *msiri*.
  - *Shamba*: banana-based homegardens intercropped with beans, coffee, tomato and eggplant, etc.
  - *Msiri*: former grassland used for cultivation of annual crops like maize, beans, etc.; including a part for vegetable production (called 'kitchen garden')

  → **SWIM-based analysis only considers the *msiri*.**

Then, the **cropping system** was defined and the **'way of farming'** was described. The **specific assumptions** for this include:

- **Size of land**: 0.125 ha of *msiri*
- **Soil classification**: based on soil data from the local field experiment (Table A6.1, which is based on the work presented in Chapter 3 of the present dissertation).
- **Analysed crop**: maize cultivar STUKA, which is typically a medium maturing cultivar (i.e. on average 111 days until maturity).
- **Cropping rhythm**: two cultivation periods (seasons) per year.
- **Cropping plan**:
  - Dates of sowing and fertilizer applications have been assumed on the basis of local practices and expert recommendations (Table A6.2).
  - Date of harvesting is determined by SWIM[2].
- **Fertilizer applications** respectively **nutrient inputs**:
  - The scenarios analysed differed regarding the use of fertilizers and hence the analysed recycling practice (Table A6.2).
  - Nutrient additions occurred in the form of mulching with crop residues, application of biogas slurry or CaSa-compost, application of urine, application of grass for carpeting (at the end of the rain season) (Tables A6.5-E.8)
  - The date of application is provided as the number of the day in the year (Table A6.3).
  - Nutrient additions [kg ha^{-1}] include application of N_{min}, N_{org}, and P_{tot}
  - Nutrient additions for each scenario are model-based estimations of the different fertilisation strategies analysed in a previous study combining material flow analysis and soil nutrient balancing (Chapter 5 in the dissertation).
  - The total input of N_{org} and N_{min} through the various applications of fertilizers/soil amenders was determined from the content of N_{tot}, which derived from the model-based estimations of annual N-inputs calculated in P4 (Table A6.4).

Table A6.2: Analysed scenarios with the assumed fertilization strategies and respective fertilizer application*

Scenario	Name	Fertilizer application for maize
AM1	'current state'	none
AM2	biogas-scenario	biogas slurry and urine
AM3	*optimistic* CaSa-scenario	CaSa-compost and urine
AM4	*pessimistic* CaSa-scenario	CaSa-compost and urine

* In addition, grass was applied as carpeting material and harvest residues were used as mulching material in all scenarios.

[2] Table E.2 presents only an estimate of the harvest period based on the sowing data combined with the average maturing period of STUKA.

Table A6.3: Input data provided for land management regarding specific dates relevant for cultivation

Season	1st season		2nd season	
	Date	Day number	Date	Day number
Mulching	2.2.	33	7.7.	210
Sowing	8.3.	67	1.10.	274
Application CaSa- compost		60 (=67-7)		267 (=274-7)
1st application of biogas slurry		95 (=67+28)		302 (=274+28)
2nd application of biogas slurry		109 (=67+42)		316 (=274+42)
Application urine		102 (=67+35)		309 (=274+35)
Application carpeting grass		112 (=67+45)		326 (=274+45)
Harvesting period	21.6.-4.7.		28.12.-12.1.	

Table A6.4: Estimation of the inputs of N_{min} and N_{org} depending on the calculated input of N_{tot} from the model in P4

	N_{min} in % of N_{tot}	N_{org} in % of N_{tot}
Mulching	20%	80%
Carpeting	20%	80%
Biogas slurry	84%	16%
CaSa-compost	25%	75%
Urine	100%	0%

Table A6.5: Input data for nutrient applications in the scenario of the current state AM1

Scenario AM1		N_{min} kg ha^{-1}	N_{org} kg ha^{-1}	P_{tot} kg ha^{-1}
Per season	Mulching	1.5	6.1	2.1
Per season	Carpeting	0.5	2.1	0.5
Per year	Total of both seasons	4.1	16.5	5.1

Table A6.6: Input data for nutrient applications in the BiogaST-scenario AM2

Scenario AM2		N_{min} kg ha^{-1}	N_{org} kg ha^{-1}	P_{tot} kg ha^{-1}
Per season	Mulching	2.5	9.8	3.5
Per season	Biogas slurry (1st application)	15.2	2.9	5.0
Per season	Urine	11.3	0.0	1.3
Per season	Biogas slurry (2nd application)	15.2	2.9	5.0
Per season	Carpeting	0.5	2.1	0.5
Per year	Total of both seasons	89.4	35.5	30.5

Table A6.7: Input data for nutrient applications in the *optimistic* CaSa-scenario AM3

Scenario AM3		N_{min} kg ha^{-1}	N_{org} kg ha^{-1}	P_{tot} kg ha^{-1}
Per season	Mulching	4.7	19.0	6.3
Per season	Urine	6.5	0.0	0.7
Per season	Carpeting	0.5	2.1	0.5
Per year	CaSa-compost	19.8	59.9	35.8
Per year	Total of both seasons	*43.3*	*102.1*	*50.8*

Table A6.8: Input data for nutrient applications in the *pessimistic* CaSa-scenario AM4

Scenario AM4		N_{min} kg ha^{-1}	N_{org} kg ha^{-1}	P_{tot} kg ha^{-1}
Per season	Mulching	3.0	12.2	4.3
Per season	Urine	3.9	0.0	0.4
Per season	Carpeting	0.5	2.1	0.5
Per year	CaSa-compost	19.3	58.5	35.1
Per year	Total of both seasons	34.3	87.1	45.4

A6.4. Output data

We selected the following **parameters** as output data from SWIM:

- Crop yields, i.e. yield of maize grains,
- Soil N, including N_{org} (anora) and N_{min} (ano3)
- Soil P, including P_{org} (porg) and P_{lab} (plab); and
- values of four plant stress factors, including W-, T-, N-, and P-stress.

The modelling was done at PIK and with the help of C. Gornott. SWIM was run for all scenarios separately and for both soil profiles. We received output data sets from SWIM in the form of raw print files (.prn), which we then imported to Excel for data evaluation. From there, we first calculated the average values for all parameters as means of the output data for the two soils that have been modelled. Then, we further evaluated the data.

A6.5. Evaluation of output data

Data evaluation and visualisation of output data was carried out in Excel®. During data evaluation, I cut of the first 13 years of the modelling. This is common practice when working with SWIM. According to C. Gornott, the model is usually running more stable after an initial period of about 10 to 15 years. Data evaluation included:

- Calculating the minimum, maximum, and mean values of all output parameters,
- Visualizing the results over time (from 1993 until 2013) in color-coded line charts, and
- Determining linear trend lines to depict a prognosis of potential changes in the soil over time depending on the fertilization practice analysed.

Results are presented in Section 7.2.2 in the main text of the present dissertation (Figs 7.2-7.4). Detailed data sets, including the plot data to Figs 7.2-7.4, are available on demand. Please write an email to: krause@ztg.tu-berlin.de

For discussing the results with respect to the practical relevance of my findings and in the context of my research objectives, I estimated **the potential for P-replenishment** in the four scenarios analysed in SWIM. Therefore, the *annual P-replenishment rate* ΔP in kg ha^{-1} yr^{-1} was calculated as follows:

$$\Delta P = \frac{P\,(t_{max}\,in\,2011) - P\,(t_{min}\,in\,1993)}{y_{sim}} \qquad \text{Eq. E.1}$$

with:

$P\,(t_{max}\,in\,2011)$	Values of soil P at the end of the last year of the simulation, which was 2011, in kg ha^{-1}
$P\,(t_{min}\,in\,1993)$	Values of soil P at the beginning of the first year of the simulation, which was 1993, in kg ha^{-1}
y_{sim}	Number of years from 1993 to 2011, which was 18 years, in yr.

The *years required for P-replenishment*, thus, to reach a certain target value of soil P, were calculated as follows:

$$Y_{Rep} = \frac{P_{target} - P_{start}}{\Delta P} \qquad \text{Eq. E.2}$$

with:

P_{target}:	Target value of soil P in kg ha^{-1}
P_{start}	Initial value of soil P in the local Andosol in kg ha^{-1}
Y_{Rep}	Years required for P-replenishment in the local soil in yr.

Data collected on target values of soil P (P_{target}) refer to a P-content in arable soil provided in mg kg^{-1} in DM of soil (Table A6.9). As the ΔP is indicated in kg ha^{-1} yr^{-1}, I further had to transfer the target values into areal data. Therefore, I considered the soil's bulk density is 0.94, 0.88, and 1.08 g cm^{-3} (of dry matter (DM)), respectively, in soil horizon 1, 2, and 3 (Krause et al., 2016).

Hence, the weight of a soil layer of 1 m is approximately 1,018 kg m^{-2}, which was rounded off to 1,000 kg m^{-2}. This in turn finally means that a P-concentration of, for example, 10 mg kg^{-1} in DM of soil is equivalent to a P-content of 10 g m^{-2} or 100 kg ha^{-1}.

Table A6.9: Values of soil P considered in the discussion of my findings with respect to the potential for replenishing soil P

	mg kg^{-1} in DM of soil	kg ha^{-1}	Source	Comment
Initial value		4	Krause et al. (2016)	current P-content in the local soil
Target value: Optimum 1	10	100	Landon (1991)	adequate P-supply for most African soils
Target value: Optimum 2	20	200	Landon (1991)	
Target value: Optimum 3	40	400	Finck (2007)	to ensure an adequate supply of P for plants
Target value: Optimum 4	80	800	Finck (2007)	
Target value: Terra Preta	250	2500	Falcão et al. (2009)	

A6.6. Additional results

In addition to the results presented in the dissertation, the evaluated output data for N_{min} is presented in Table A6.10. Simulated concentrations of N_{min} in the soil fluctuate widely over the two decades (i.e. range of $\Delta_{min.}^{max.}$), as was to be expected pursuant to Finck (2007). The mean value over two decades, simulating BiogaST and CaSa scenarios, is nearly seven and four times higher compared to the current state, respectively.

Table A6.10: Output data for the parameter N_{min} (i.e. NO_3).

Scenario	NO_3 (mean value) kg ha^{-1} yr^{-1}	NO_3 (range of $\Delta_{min.}^{max.}$) kg ha^{-1} yr^{-1}	Relative change of the mean value compared to the current state % of AM1
AM1	2.4	0.0-42.4	100 %
AM2	18.0	0.0-115.0	766 %
AM3	10.3	0.0-93.6	439 %
AM4	8.3	0.0-79.0	353 %

Furthermore, in all scenarios, maize plants are in particular stressed by limited availability of water (Table A6.11). Compared to the current state of affairs, fertilizing strategies analysed in AM2 (BiogaST-scenario) or AM3+4 (CaSa-scenarios) have the potential to slightly reduce WS. Second severe is nutrient stress whilst in AM1, NS is more severe compared to PS. Using biogas slurry or CaSa-compost as soil amenders, however, reduces existing NS compared to the current state of affairs. On the contrary, PS existing in AM2-4 is not reduced but rather increases compared to AM1. I assume that in the simulation, increased plant growth corresponds with higher plant uptake of P, which in turn reduces soil P and ultimately causes PS. Finally, plants hardly suffer from TS, in none of the scenarios, as it was to be expected for agriculture under tropical savanna climate.

Table A6.11: Estimations of specific growth constraints through SWIM-modelling including water stress (WS), temperature stress (TS), and nutrient stress for N (NS) and P (PS); stress factors vary from 0: `stress' to 1: `no stress'; values displayed are means of 20 years simulation.

Scenario	WS	TS	NS	PS
AM1	0.65	0.97	0.63	0.75
AM2	0.68	0.97	0.93	0.69
AM3	0.67	0.97	0.85	0.70
AM4	0.67	0.97	0.81	0.71

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LIST OF ABBREVIATIONS

DM	Dry matter
N	Nitrogen
NS	Nitrogen stress
P	Phosphorus
PIK	Potsdam Institute for Climate Impact Research
PS	Phosphorus stress
SWIM	Soil and Water Integrated Model
TS	Temperature stress
ua.	Unanalysed
WS	Water stress

Abbreviations of selected output parameters:

ano3	Nitrate
anora	Mineralisable organic N
plab	Labile P
porg	Organic P

Abbreviations of parameters in equations:

BAD	Above-ground biomass
BE	Crop-specific parameter for converting energy to biomass
Δ BE	Daily potential increase in total biomass
HI	Harvest index
HUNA	Accumulation of daily heat units
IHUN	Heat unit index
PAR	Photosynthetic active radiation
PHUN	Potential heat units required for the maturity of the crop
P_{target}	Target values of soil P
REGF	Crop growth regulating factor
YLD	Crop yield

Chapter 3

Supplements

S1: Supplement of P2

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Supplement of

Organic wastes from bioenergy and ecological sanitation as a soil fertility improver: a field experiment in a tropical Andosol

A. Krause et al.

Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

Table S1. Provision of plot data for Fig. 2: untreated Andosol and soil treated with biogas slurry, compost, and CaSa-compost; measured using ceramic pressure plates.

	pF	θ	Error (θ)
Andosol ceramic plate	0	0,593	0,013
	1,8	0,357	0,014
	2,5	0,292	0,014
	3	0,262	0,007
	4,2	0,228	0,022
Biogas slurry	0	0,621	0,022
	1,8	0,355	0,028
	2,5	0,294	0,028
	3	0,268	0,025
	4,2	0,221	0,021
Compost	0	0,634	0,045
	1,8	0,344	0,028
	2,5	0,286	0,025
	3	0,250	0,041
	4,2	0,227	0,022
CaSa-compost	0	0,594	0,029
	1,8	0,353	0,021
	2,5	0,290	0,015
	3	0,265	0,015
	4,2	0,223	0,020

Table S2: Fitted parameters of the PDI model of the untreated Andosol version of the unconstrained Mualem-van Genuchten (MvG) model, curve shown in Fig. 2.

fitted Parameter	Unit	Value	Min	Max	2.5%	97.5%
alpha	1 cm^{-1}	0.0441	0.00001	0.5	0.0361	0.0538
n	-	3	1.01	15	2,622	4,622
th_r	$cm^3\ cm^{-3}$	0.358	0	0.4	0.352	0.364
th_s	$cm^3\ cm^{-3}$	0.556	0.1	1	0.55	0.562

with pF(dry) set to 6.8 and a set to -1.5

Table S3. Provision of plot data for Fig. 3: Total above-ground biomass production and marketable crop yields given as g per plot.

Total above-ground biomass production [g $plot^{-1}$]	Onion		Carrot		Cabbage		Beans		Maize	
Control Andosol	880	a	1312	a	no		192	a	7177	a
Biogas slurry	1211	ab	2439	a	7417	b	360	ab	10028	a
Compost	1679	b	2991	a	8571	b	518	b	11086	ab
CaSa-Compost	1516	ab	2169	a	9390	b	1244	c	15173	b

Yields of food crops [g $plot^{-1}$]	Onion bulb (air-dried)		Carrot (fresh)		Head of Cabbage (fresh)		Beans		Maize grains (air-dried)	
Control Andosol	444	a	918	a			n.a.		497	a
Biogas slurry	691	ab	1707	a	4320	b	n.a.		1181	ab
Compost	1056	b	2093	a	4950	b	n.a.		1431	bc
CaSa-Compost	1088	b	1518	a	6101	b	n.a.		1973	c

Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha=0.05$; n=4 for the untreated control plots and n=5 for the amended plots). n.a. not available

Table S4. Provision of plot data for Fig. 4: Total nutrient concentration in DM, total nutrient uptake, and air-dry grain yield. The response levels (relative nutrient concentration, relative nutrient uptake, and relative biomass) are given relative to the control treatment's performance, which was set 100 %.

	Total nutrient concentration in dry maize grains						Relative nutrient concentration in dry maize grains					
	N	P	K	Ca	Mg	Zn	N	P	K	Ca	Mg	Zn
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	%	%	%	%	%	%
Control Andosol	15,9	2,3	4,4	0,1	1,0	22,1	100,0	100,0	100,0	100,0	100,0	100,0
Biogas slurry	16,5	2,6	4,0	0,1	1,0	18,0	103,6	113,5	91,5	74,8	97,9	81,4
Compost	15,6	2,5	3,6	0,1	1,0	19,0	98,2	108,4	82,9	82,3	99,2	86,1
CaSa-Compost	16,8	3,0	3,9	0,1	1,1	18,2	105,8	128,8	88,2	75,8	109,4	82,3

	Total nutrient uptake in dry maize grains						Relative nutrient uptake in dry maize grains					
	N	P	K	Ca	Mg	Zn	N	P	K	Ca	Mg	Zn
	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	g $plant^{-1}$	mg $plant^{-1}$	%	%	%	%	%	%
Control Andosol	0,33	0,05	0,09	0,00	0,02	0,46	100,0	100,0	100,0	100,0	100,0	100,0
Biogas slurry	0,79	0,13	0,19	0,00	0,05	0,87	240,8	263,6	212,6	173,9	227,5	189,1
Compost	1,13	0,18	0,27	0,01	0,07	1,38	343,8	379,4	290,3	288,0	347,2	301,5
CaSa-Compost	1,51	0,27	0,35	0,01	0,10	1,63	456,1	555,2	380,2	326,5	471,4	354,7

	Total biomass air-dry grain yield g $plant^{-1}$	Relative biomass air-dry grain yield %
Control Andosol	33,0	100
Biogas slurry	68,0	206
Compost	89,6	271
CaSa-Compost	119,1	361

Different letters reflect means differing significantly from one another (HSD, Tukey test, α=0.05; n=3).

Fig. S1. The soil profile. The blade of the machete was ~0.3 m
The photograph was taken by A. Krause on February 2nd, 2014.

Fig. S2. The experimental site - 10 days after initiating the experiment with sowing of maize.
The photograph was taken by A. Krause on March 14th, 2014.

Fig. S3. The experimental site - 22 days after initiating the experiment with sowing of maize.
The photograph was taken by A. Krause on March 26th, 2014.

Fig. S4. The experimental site - 30 days after initiating the experiment with sowing of maize.
The photograph was taken by A. Krause on May 2nd, 2014.

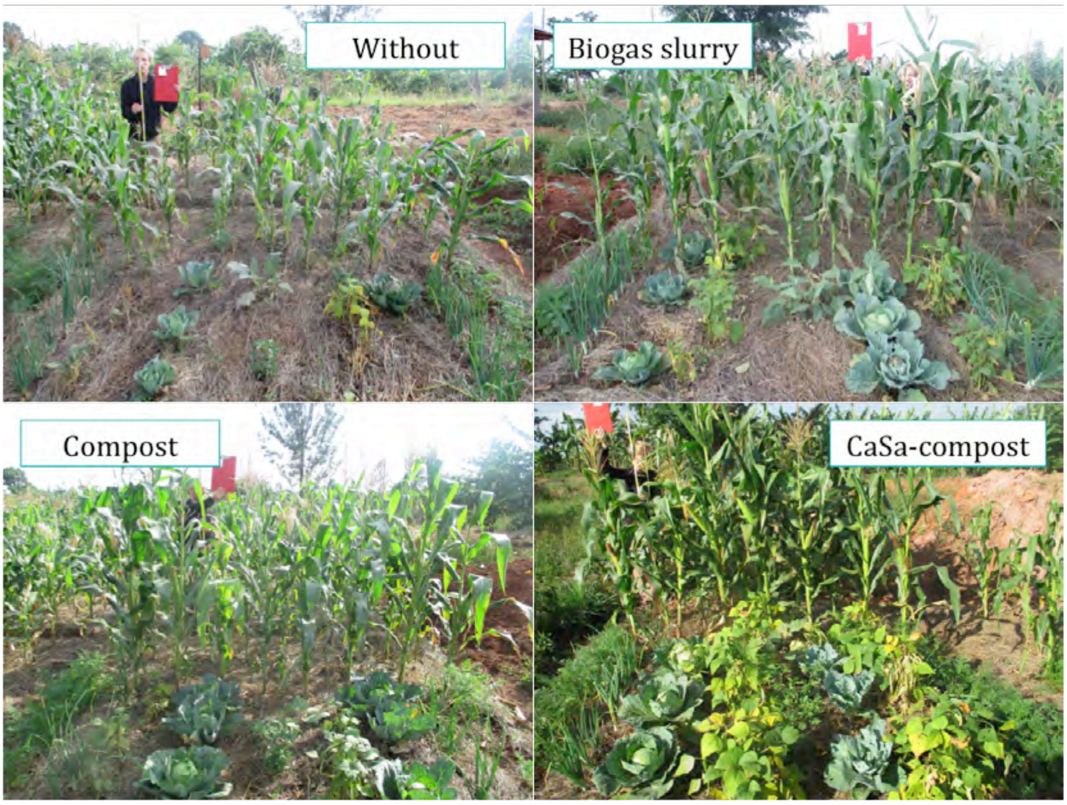

Fig. S5. Progress of the experiment - 60 days after initiating the experiment with sowing of maize: an untreated plot (without) compared to plots amended with biogas slurry, compost and CaSa-compost.
These photographs were taken by A. Krause on June 2nd, 2014.

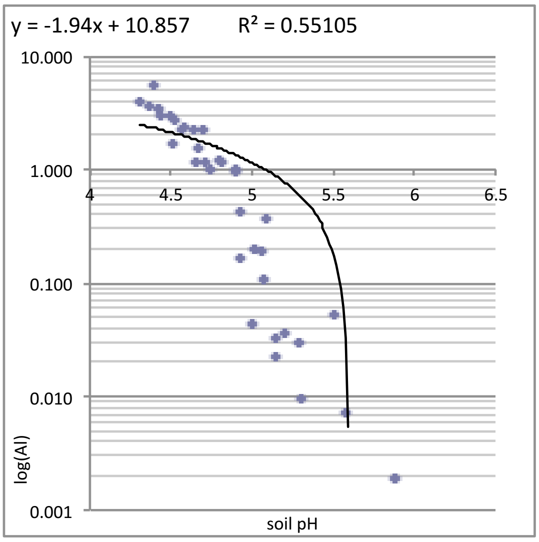

Fig. S6. Regression analysis: concentration of exchangeable Al against the pH for discussion in Sect. 3.5.

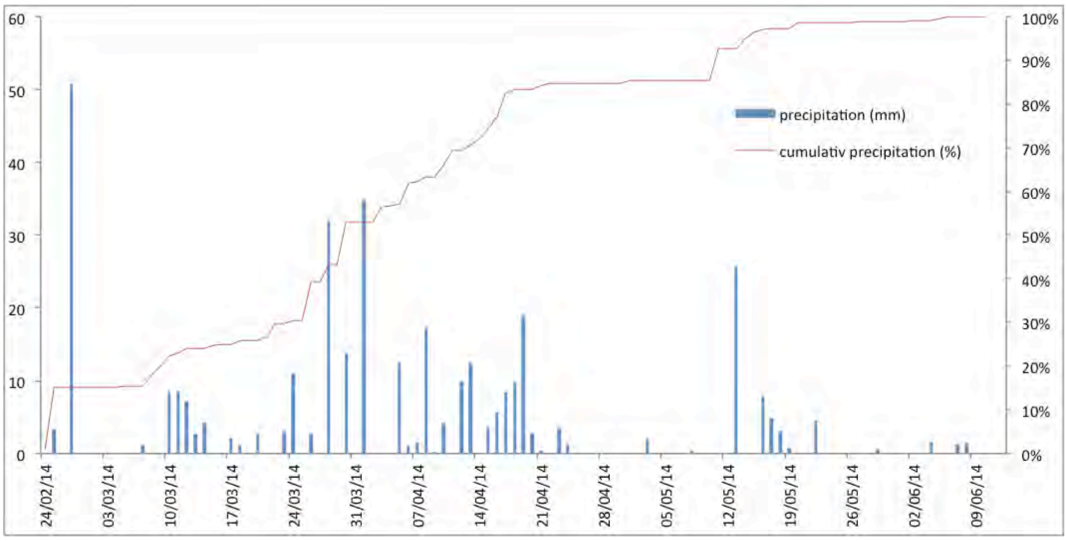

Fig. S7. Daily precipitation in mm (right-hand ordinate) and cumulative precipitation in % (left-hand ordinate) during the course of the experiment from February to June 2014.

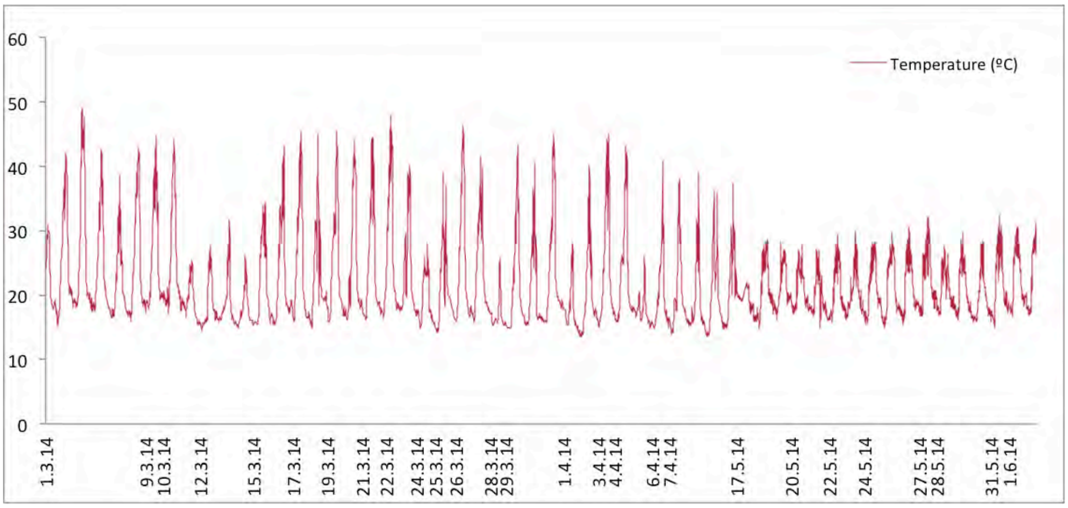

Fig. S8. Daily temperatures in ° C during the course of the experiment from March to June 2014.

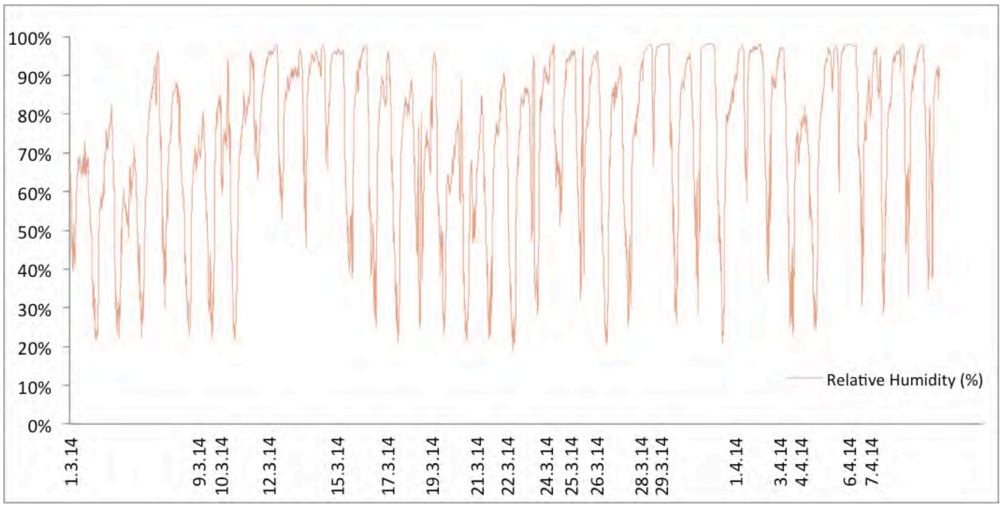

Fig. S9. Daily humidity in % during the course of the experiment from March to May 2014; in June it was not measured due to technical problems with the device.

S2: Supplement of P3

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SUPPLEMENTARY MATERIAL OF

Linking Energy-Sanitation-Agriculture: Intersectional Resource Management in Smallholder Households in Tanzania

A. Krause, V. S. Rotter
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

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Results of the evaluation of data collected from water boiling tests (WBT) with the stoves selected for modelling the micro energy system (MES)

Selected stoves are described and abbreviations defined in Table 2 of the main text and Table A.2.

Table S.1: Efficiency in % (i.e. energy used in % of total energy consumed) and fuel consumption in g of dry matter (DM); data were derived from evaluated WBT-data and used to characterize the selected stoves; plot data for Fig. A.10.

	Efficiency [%]			Fuel consumption [g]		
Stove	HP_cold	HP_hot	LP	HP_cold	HP_hot	LP
3SF	15.9 ± 2.3	14.3 ± 0.2	17.5 ± 1.5	784 ± 126	810 ± 86	894 ± 86
CB	22.9 ± 0.8	41.5 ± 2.1	38.8 ± 3.4	272 ± 15	176 ± 13	205 ± 12
RS	24.8 ± 0.5	33.7 ± 1.5	29.7 ± 0.8	547 ± 15	408 ± 28	460 ± 30
SG	22.6 ± 0.3	22.6 ± 0.3	19.2 ± 0.6	486 ± 8	486 ± 8	823 ± 23
TLUD	24.9 ± 0.6	24.9 ± 0.6	17.2 ± 0.8	440 ± 8	440 ± 8	782 ± 21
BGB	48.1 ± 0.5	48.1 ± 0.5	40.9 ± 0.5	265 ± 3	265 ± 3	426 ± 4
Average	26.5 ± 0.4	30.8 ± 0.4	27.2 ± 0.7	466 ± 21	431 ± 15	598 ± 16

Non-common abbreviations: 3SF: three stone fire; BGB: biogas burner; CB: charcoal burner; DM: dry matter; HP: high power phase; LP: low power phase; RS: rocket stove; SG: sawdust gasifier; TLUD: top-lit updraft gasifier; WBT: water boiling test.

Table S.2: Average cooking power in kW and "corrected time to boil" in minutes; data were derived from evaluated WBT-data and used to characterize the selected stoves; plot data for Fig. A.11.

	Average cooking power [kW]			Time to boil, corr. [min]	
Stove	HP_cold	HP_hot	LP	HP_cold	HP_hot
3SF	1.0 ± 0.1	1.4 ± 0.2	1.3 ± 0.3	34.7 ± 2.4	25.7 ± 1.8
CB	0.8 ± 0.1	1.5 ± 0.1	0.9 ± 0.1	34.9 ± 1.9	21.3 ± 1.0
RS	0.8 ± 0.0	1.5 ± 0.1	0.9 ± 0.0	49.7 ± 2.9	24.2 ± 1.8
SG	1.6 ± 0.1	1.6 ± 0.1	1.0 ± 0.0	20.7 ± 1.0	20.7 ± 1.0
TLUD	1.5 ± 0.1	1.5 ± 0.1	0.9 ± 0.0	22.3 ± 1.2	22.3 ± 1.2
BGB	1.6 ± 0.0	1.6 ± 0.0	1.0 ± 0.0	21.5 ± 0.7	21.5 ± 0.7
Average	1.2 ± 0.0	1.5 ± 0.0	1.0 ± 0.1	30.6 ± 0.8	22.6 ± 0.5

Non-common abbreviations: 3SF: three stone fire; BGB: biogas burner; CB: charcoal burner; corr.: corrected; HP: high power phase; LP: low power phase; RS: rocket stove; SG: sawdust gasifier; TLUD: top-lit updraft gasifier; WBT: water boiling test.

Table S.3: Total energy consumption in MJ and "energy delivered to the cooking pot" (i.e. energy used) in MJ; data were derived from evaluated WBT-data and used to characterize the selected stoves.

	Energy consumed [MJ]		Energy to cooking pot [MJ]		
Stove	HP_cold	LP	HP_cold	HP_hot	LP
3SF	14.1 ± 2.3	16.2 ± 1.6	2.1 ± 0.1	2.2 ± 0.2	3.5 ± 0.8
CB	7.8 ± 0.4	5.9 ± 0.4	1.6 ± 0.1	1.9 ± 0.1	2.3 ± 0.2
RS	9.5 ± 0.3	7.9 ± 0.6	2.3 ± 0.1	2.2 ± 0.1	2.3 ± 0.1
SG	8.8 ± 0.1	14.3 ± 0.4	1.9 ± 0.0	1.9 ± 0.0	2.7 ± 0.1
TLUD	8.1 ± 0.2	14.4 ± 0.4	1.9 ± 0.0	1.9 ± 0.0	2.4 ± 0.1
BGB	4.1 ± 0.0	6.4 ± 0.1	1.9 ± 0.0	1.9 ± 0.0	2.7 ± 0.1
Average	8.7 ± 0.4	10.8 ± 0.3	2.0 ± 0.0	2.0 ± 0.0	2.7 ± 0.1

Non-common abbreviations: 3SF: three stone fire; BGB: biogas burner; CB: charcoal burner; DM: dry matter; HP: high power phase; LP: low power phase; RS: rocket stove; SG: sawdust gasifier; TLUD: top-lit updraft gasifier; WBT: water boiling test.

System analysis of material flows: results of modelling the MES

Table S.4: Energy usage in the model household for the defined cooking task, described as “energy to cooking pot” (i.e. energy used) and total energy consumption, per household and expressed in MJ per day and GJ per year.

	Energy to cooking pot				Total energy consumed			
Alternative	MJ hh^{-1} d^{-1}		GJ hh^{-1} yr^{-1}		MJ hh^{-1} d^{-1}		GJ hh^{-1} yr^{-1}	
E1	14.7	± 2.8	5.4	± 1.0	76.9	± 9.4	28.1	± 3.4
E2	10.5	± 0.9	3.8	± 0.3	33.1	± 1.9	12.1	± 0.7
E3	11.4	± 0.6	4.2	± 0.2	42.5	± 2.2	15.5	± 0.8
E4	11.9	± 0.4	4.4	± 0.1	60.5	± 1.4	22.1	± 0.5
E5	11.0	± 0.4	4.0	± 0.1	59.2	± 1.5	21.6	± 0.5
E6	11.7	± 0.2	4.3	± 0.1	27.3	± 0.2	12.1	± 0.7
Average (E1-E6)	11.9	± 0.5	4.3	± 0.2	49.9	± 1.7	18.2	± 0.6

Abbreviations of the alternatives are defined in Table 2 of the main text. Non-common abbreviations: hh: household.

Table S.5: Carbon and nutrient (i.e. N and P) recovery rate in % of total input of the respective substance.

	Recovery rates					
Alternative	% C		% N		% P	
E1 (ash)	0.00	± 0.00	0.00	± 0.00	1.00	± 0.00
E2.1. (ash & brands)	0.04	± 0.02	0.03	± 0.01	0.79	± 0.28
E2.2. (ash)	0.00	± 0.00	0.00	± 0.00	1.00	± 0.00
E3 (ash)	0.00	± 0.00	0.00	± 0.00	1.00	± 0.00
E4 (ash & char)	0.37	± 0.04	0.29	± 0.11	1.00	± 0.39
E4* (ash & char)	0.15	± 0.05	0.00	± 0.00	1.00	± 0.00
E5 (ash & char)	0.35	± 0.04	0.22	± 0.09	1.00	± 0.27
E5* (ash & char)	0.04	± 0.01	0.00	± 0.00	1.00	± 0.00
E6.1. (biogas slurry, rem)	0.25	± 0.11	0.42	± 0.17	0.53	± 0.20
E6.1. (biogas slurry, over)	0.27	± 0.15	0.42	± 0.22	0.47	± 0.26
E6.1. (biogas slurry, sum)	0.52	± 0.19	0.85	± 0.28	1.00	± 0.33

Abbreviations of the alternatives are defined in Table 2 of the main text. Non-common abbreviations: hh: household; rem: biogas slurry removed; over: biogas slurry output via overflow; sum: total outflow of biogas slurry from biogas digester.

Table S.6: Material output flows of gaseous emissions; total emissions are expressed on layers of goods and substance C in kg per household and year; figures after data reconciliation in STAN.

Alternative	Total emissions kg hh^{-1} yr^{-1}		Total emissions kg C hh^{-1} yr^{-1}		GHG emissions kg CO_2e hh^{-1} yr^{-1}		CO_2 kg hh^{-1} yr^{-1}		CO kg hh^{-1} yr^{-1}		N_2 kg hh^{-1} yr^{-1}		NO kg hh^{-1} yr^{-1}		CH_4 kg hh^{-1} yr^{-1}		TNMHC kg hh^{-1} yr^{-1}		N_2O kg hh^{-1} yr^{-1}	
E1	3878	± 383	763	± 103	2742	± 377	2707	± 376	57	± 8	1.7	± 0.3	7.2	± 1.3	NA	NA	NA	NA	NA	NA
E2.1.	1644	± 1178	429	± 330	1509	± 254	706	± 214	81	± 21	NA	NA	NA	NA	18	± 4	30	± 9	NA	NA
E2.2.	1162	± 106	285	± 29	1041	± 105	974	± 105	45	± 5	0.5	± 0.1	2.1	± 0.3	NA	NA	NA	NA	NA	NA
E2 (total)	2806	± 1182	714	± 331	2551	± 275	1680	± 238	126	± 22	0.5	± 0.1	2.1	± 0.3	18	± 4	30	± 9	NA	NA
E3	2120	± 138	417	± 37	1497	± 214	1483	± 136	29	± 3	0.9	± 0.2	4.0	± 0.7	NA	NA	NA	NA	NA	NA
E4	2169	± 317	387	± 8	1401	± 315	1340	± 314	49	± 11	0.8	± 0.3	3.3	± 1.1	NA	NA	NA	NA	NA	NA
E4 (morning)	583	± 336	135	± 91	481	± 335	496	± 335	NA	NA	0.3	± 0.1	1.3	± 0.5	NA	NA	NA	NA	NA	NA
E4*	2752	± 462	522	± 92	1882	± 460	1836	± 459	49	± 11	1.1	± 0.3	4.6	± 1.2	NA	NA	NA	NA	NA	NA
E5	2117	± 287	375	± 8	1336	± 285	1347	± 285	18	± 4	1.0	± 0.2	4.3	± 1.0	NA	NA	NA	NA	NA	NA
E5 (morning)	739	± 279	180	± 26	648	± 277	661	± 277	NA	NA	0.3	± 0.1	1.2	± 0.4	NA	NA	NA	NA	NA	NA
E5*	2856	± 400	556	± 27	1984	± 398	2008	± 397	18	± 4	1.3	± 0.3	5.5	± 1.1	NA	NA	NA	NA	NA	NA
E6.1.	1622	± 17	290	± 4	1064	± 14	209	± 70	NA	NA	NA	NA	NA	NA	186	± 47	NA	NA	1.5	± 0.6
E6.2.	432	± 95	191	± 47	5805	± 1340	1064	± 14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
E6 (total)	2054	± 96	482	± 47	6870	± 1340	1274	± 71	NA	NA	NA	NA	NA	NA	186	± 47	NA	NA	1.5	± 0.6

Abbreviations of the alternatives are defined in Table 2 of the main text. Non-common abbreviations: CO_2e: carbon dioxide equivalent; GHG: greenhouse gas; hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis"); TNMHC: total non-methane hydrocarbons.

Table S.7: Material output flows of emissions with global warming potential (GWP); emissions are expressed in kg CO_2-equivalents per household and year, assessed with GWP-factors presented in Table A.6; plot data for Fig. 5a.

Alternative	GHG emissions kg CO_2e hh^{-1} yr^{-1}		CO_2 kg hh^{-1} yr^{-1}		CO kg hh^{-1} yr^{-1}		NO kg hh^{-1} yr^{-1}		CH_4 kg hh^{-1} yr^{-1}		TNMHC kg hh^{-1} yr^{-1}		N_2O kg hh^{-1} yr^{-1}	
E1	2742	± 377	2707	± 376	115	± 16	-80	± 14	NA	NA	NA	NA	NA	NA
E2.1.	1509	± 254	706	± 214	163	± 42	NA	NA	508	± 125	133	± 40	NA	NA
E2.2.	1041	± 105	974	± 105	90	± 10	-23	± 3	NA	NA	NA	NA	NA	NA
E2 (total)	2551	± 275	1680	± 238	253	± 43	-23	± 3	508	± 125	133	± 40	NA	NA
E3	1497	± 214	1483	± 136	57	± 5	-44	± 7	NA	NA	NA	NA	NA	NA
E4	1401	± 315	1340	± 314	97	± 23	-36	± 12	NA	NA	NA	NA	NA	NA
E4 (morning)	481	± 335	496	± 335	NA	NA	-15	± 6	NA	NA	NA	NA	NA	NA
E4*	1882	± 460	1836	± 459	97	± 23	-51	± 13	NA	NA	NA	NA	NA	NA
E5	1336	± 285	1347	± 285	36	± 8	-47	± 11	NA	NA	NA	NA	NA	NA
E5 (morning)	648	± 277	661	± 277	NA	NA	-13	± 5	NA	NA	NA	NA	NA	NA
E5*	1984	± 398	2008	± 397	36	± 8	-60	± 12	NA	NA	NA	NA	NA	NA
E6.1.	1064	± 14	209	± 70	NA	NA	NA	NA	5195	± 1327	NA	NA	401	± 169
E6.2.	5805	± 1340	1064	± 14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
E6 (total)	6870	± 1340	1274	± 71	NA	NA	NA	NA	5195	± 1327	NA	NA	401	± 169

Abbreviations of the alternatives are defined in Table 2 of the main text. Non-common abbreviations: CO_2e: carbon dioxide equivalent; GHG: greenhouse gas; hh: household; NA: not analysed; TNMHC: total non-methane hydrocarbons.

Table S.8: Material output flows of emissions with eutrophication potential (EP); emissions are expressed in kg PO_4-equivalents per household and year, assessed with the EP-factors presented in Table A.7; plot data for Fig. 5b.

	Total emissions with EP		NO		NH_3	
Alternative	kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}	
E1	0.9	± 0.2	0.9	± 0.2	NA	NA
E2.1.	NA	NA	NA	NA	NA	NA
E2.2.	0.3	± 0.0	0.3	± 0.0	NA	NA
E2 (total)	0.3	± 0.0	0.3	± 0.0	NA	NA
E3	0.5	± 0.1	0.5	± 0.1	NA	NA
E4	0.4	± 0.1	0.4	± 0.1	NA	NA
E4 (morning)	0.2	± 0.1	0.2	± 0.1	NA	NA
E4*	0.6	± 0.2	0.6	± 0.2	NA	NA
E5	0.6	± 0.1	0.6	± 0.1	NA	NA
E5 (morning)	0.2	± 0.1	0.2	± 0.1	NA	NA
E5*	0.7	± 0.1	0.7	± 0.1	NA	NA
E6.1.	2.9	± 1.2	NA	NA	2.9	± 1.2
E6.2.	NA	NA	NA	NA	NA	NA
E6 (total)	2.9	± 1.2	NA	NA	2.9	± 1.2

Abbreviations of the alternatives are defined in Table 2 of the main text.
Non-common abbreviations: NA: not analysed.

Table S.9: Plausibility check of results for material output flows of GHG emissions in kg CO_2-equivalents per household and year compared with literature; assessed with the GWP-factors presented in Table A.6; plot data for Fig. S.6.

	GHG emissions [kg CO_2e hh^{-1} yr^{-1}]		
Alternative	Our calculations	Calculations acc. to literature	Source
E1	2742	3638	Smith et al., 2000, Table 4*
E3	1497	1862	Smith et al., 2000, Table 4**
E4	1401	1948	Smith et al., 2000, Table 4**
E5	1336	1799	Smith et al., 2000, Table 4**
E6	1064	1752	Smith et al., 2000, Table 4
LPG	NA	573	Smith et al., 2000, Table 4
Electricity Germany	NA	3403	Atlantic consulting, 2009
Electricity Europe	NA	2297	Atlantic consulting, 2009

Abbreviations of the alternatives are defined in Table 2 of the main text. Non-common abbreviations: CO_2e: carbon dioxide equivalent; GHG: greenhouse gas; hh: household; GWP: global warming potential; LPG: liquefied petroleum gas; NA: not analysed.
*Values taken for acacia and three-stone fire; **values taken for acacia and "improved metal stove" (imet).

System analysis of material flows: results of modelling the micro sanitation system (MSS)

Analysed scenarios are defined in Table 3 of the main text.

Table S.10: Material input flows of resources; results are expressed on layers of goods and in kg of fresh matter (FM) per household and year; figures after data reconciliation in STAN; plot data for Fig. S.7.

	Faeces	Urine	Cleansing water	Disposal of grey water	Dry material	Sum air demand	Fuel 1 (sawdust)	Fuel 2 (firewood)	Flush water
Alternative	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}	kg hh^{-1} yr^{-1}
S1	383 ± 122	1605 ± 285	383 ± 77	2789 ± 693	NA NA	NA NA	NA NA	NA NA	NA NA
S2	383 ± 88	1605 ± 138	383 ± 54	NA NA	205 ± 34	NA NA	NA NA	NA NA	NA NA
S3	383 ± 85	1605 ± 138	383 ± 54	NA NA	205 ± 33	721 ± 132	67 ± 26	92 ± 34	NA NA
S4	383 ± 123	1605 ± 292	383 ± 77	6609 ± 2057	NA NA	NA NA	NA NA	NA NA	15330 ± 3333
S2 (50%)	274 ± 88	1235 ± 224	274 ± 55	NA NA	147 ± 24	NA NA	NA NA	NA NA	NA NA
S3 (50%)	274 ± 88	1235 ± 224	274 ± 55	NA NA	147 ± 24	488 ± 181	47 ± 19	64 ± 25	NA NA
S2 (100%)	547 ± 127	2469 ± 213	548 ± 77	NA NA	293 ± 48	NA NA	NA NA	NA NA	NA NA
S3 (100%)	548 ± 123	2469 ± 213	548 ± 77	NA NA	293 ± 48	1043 ± 191	97 ± 37	133 ± 50	NA NA

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: FM: fresh matter; hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis").

Table S.11: Material input flows of resources; results are expressed on the layer of substance C and in kg per household and year; figures after data reconciliation in STAN; plot data for Fig. S.9.

	Faeces	Urine	Dry material	Fuel 1 (sawdust)	Fuel 2 (firewood)	Disposal of grey water	Total
Alternative	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}	kg C hh^{-1} yr^{-1}
S1	35 ± 10	13 ± 2	NA NA	NA NA	NA NA	2 ± 1	50 ± 10
S2	35 ± 10	13 ± 2	20 ± 7	NA NA	NA NA	NA NA	68 ± 12
S3	35 ± 9	13 ± 2	20 ± 7	29 ± 8	39 ± 9	NA NA	136 ± 17
S4	35 ± 10	13 ± 2	NA NA	NA NA	NA NA	4 ± 2	52 ± 10
S2 (100%)	51 ± 14	19 ± 3	29 ± 10	NA NA	NA NA	NA NA	99 ± 18
S3 (100%)	51 ± 13	19 ± 3	29 ± 10	42 ± 12	56 ± 14	NA NA	196 ± 25

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis").

Table S.12: Material input flows of resources; results are expressed on the layer of substance N and in kg per household and year; figures after data reconciliation in STAN; plot data for Fig. S.10.

	Faeces	Urine	Dry material	Fuel 1 (sawdust)	Fuel 2 (firewood)	Disposal of grey water	Total
Alternative	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}	kg N hh^{-1} yr^{-1}
S1	2.2 ± 0.7	8.2 ± 0.5	NA NA	NA NA	NA NA	0.1 ± 0.1	10.5 ± 0.8
S2	2.2 ± 0.7	8.2 ± 0.5	0.4 ± 0.1	NA NA	NA NA	NA NA	10.8 ± 0.8
S3	2.2 ± 0.6	8.2 ± 0.5	0.4 ± 0.1	0.2 ± 0.07	0.3 ± 0.11	NA NA	11.2 ± 0.8
S4	2.2 ± 0.7	8.2 ± 0.5	NA NA	NA NA	NA NA	0.3 ± 0.2	10.7 ± 0.8
S2 (100%)	3.1 ± 0.9	12.6 ± 0.8	0.6 ± 0.2	NA NA	NA NA	NA NA	16.3 ± 1.2
S3 (100%)	3.1 ± 0.8	12.6 ± 0.8	0.6 ± 0.2	0.2 ± 0.10	0.4 ± 0.16	NA NA	16.9 ± 1.2

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis").

Table S.13: Material input flows of resources; results are expressed on the layer of substance P and in kg per household and year; figures after data reconciliation in STAN; plot data for Fig. S.11.

	Faeces	Urine	Dry material	Fuel 1 (sawdust)	Fuel 2 (firewood)	Disposal of grey water	Total
Alternative	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}	kg P hh^{-1} yr^{-1}
S1	0.7 ± 0.2	0.9 ± 0.1	NA NA	NA NA	NA NA	0.1 ± 0.0	1.7 ± 0.3
S2	0.7 ± 0.2	0.9 ± 0.1	0.3 ± 0.1	NA NA	NA NA	NA NA	1.9 ± 0.3
S3	0.7 ± 0.2	0.9 ± 0.1	0.3 ± 0.1	0.0 ± 0.01	0.1 ± 0.01	NA NA	2.0 ± 0.3
S4	0.7 ± 0.2	0.9 ± 0.1	NA NA	NA NA	NA NA	0.2 ± 0.1	1.8 ± 0.3
S2 (100%)	1.0 ± 0.3	1.5 ± 0.2	0.4 ± 0.2	NA NA	NA NA	NA NA	2.8 ± 0.4
S3 (100%)	1.0 ± 0.3	1.5 ± 0.2	0.4 ± 0.1	0.0 ± 0.01	0.1 ± 0.02	NA NA	2.9 ± 0.4

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis").

Table S.14: Carbon and nutrient (i.e. N and P) recovery rate in % of total input of the respective substance

	Recovery rates		
Alternative	% C	% N	% P
S1	0.79 ± 0.21	0.18 ± 0.09	0.28 ± 0.14
S2	0.95 ± 0.22	0.97 ± 0.11	0.91 ± 0.19
S3	0.55 ± 0.10	0.93 ± 0.09	0.92 ± 0.17
S4	0.61 ± 0.14	0.09 ± 0.05	0.26 ± 0.09

Abbreviations of the alternatives are defined in Table 3 of the main text.

Table S.15: Material output flows of liquid emissions and solid emissions (i.e. precipitation in urine storage); results for liquid emissions are expressed in kg of FM and in kg of N and P per household and year; results for solid emissions are expressed in kg of P per household and year; figures after data reconciliation in STAN; plot data for Fig. S.12.

	Sum emission effluent pit		N in emission effluent pit		P in emission effluent pit		Precipitation in urine storage in UDDT	
Alternative	kg hh^{-1} a^{-1}		kg N hh^{-1} a^{-1}		kg P hh^{-1} a^{-1}		kg P hh^{-1} a^{-1}	
S1	4318	± 489	8.6	± 0.7	1.2	± 0.2	NA	NA
S2	NA	NA	NA	NA	NA	NA	0.2	± 0.1
S3	NA	NA	NA	NA	NA	NA	0.2	± 0.1
S4	23554	± 1473	9.7	± 0.5	1.3	± 0.1	NA	NA
S2 (100%)	NA	NA	NA	NA	NA	NA	0.2	± 0.1
S3 (100%)	NA	NA	NA	NA	NA	NA	0.2	± 0.1

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations; hh: household; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow ANalysis"); UDDT: urine-diverting dry toilet.

Table S.16: Material output flows of gaseous emissions; sum of emissions from volatilisation are expressed on layers of goods in kg per household and year; figures after data reconciliation in STAN; plot data for Fig. S.12.

	Sum emission volatilisation pit		Sum emission volatilisation UDDT		Sum emission volatilisation oven		GHG emissions	
Alternative	kg hh^{-1} a^{-1}		kg hh^{-1} a^{-1}		kg hh^{-1} a^{-1}		kg CO_2e hh^{-1} a^{-1}	
S1	27	± 4	NA	NA	NA	NA	218	± 55
S2	NA	NA	311	± 83	NA	NA	77	± 22
S3	NA	NA	311	± 79	877	± 132	363	± 86
S4	41	± 4	NA	NA	NA	NA	333	± 57
S2 (100%)	NA	NA	462	± 120	NA	NA	79	± 23
S3 (100%)	NA	NA	462	± 114	1268	± 191	494	± 122

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; GHG: greenhouse gas; NA: not analysed; STAN: software used for material flow analysis ("SubsTance flow Analysis"); UDDT: urine-diverting dry toilet.

Table S.17: Material output flows of emissions with global warming potential (GWP); emissions are expressed in kg CO_2-equivalents per household and year, assessed with GWP-factors as shown in Table B.5; plot data for Fig. 6a.

	Total GHG emissions		CH_4		CO_2		CO		NO	
Alternative	kg CO_2e hh^{-1} yr^{-1}		kg CO_2e hh^{-1} yr^{-1}		kg CO_2e hh^{-1} yr^{-1}		kg CO_2e hh^{-1} yr^{-1}		kg CO_2e hh^{-1} yr^{-1}	
S1	218	± 55	199	± 55	19	± 5	NA	NA	NA	NA
S2	77	± 22	70	± 22	6	± 2	NA	NA	NA	NA
S3	363	± 86	70	± 22	6	± 2	209	± 72	-3	± 2
S4	333	± 57	303	± 57	30	± 6	NA	NA	NA	NA

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; GHG: greenhouse gas; NA: not analysed.

Table S.18: Material output flows of emissions with eutrophication potential (EP); emissions are expressed in kg PO_4-equivalents per household and year, assessed with EP-factors as shown in Table B.6; plot data for Fig. 6b.

	Total emissions with EP		N-leaching		P-leaching		NH_3		NO	
Alternative	kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}		kg PO_4e hh^{-1} yr^{-1}	
S1	7.4	± 0.6	3.6	± 0.3	3.7	± 0.5	NA	NA		
S2	0.16	± 0.05	NA	NA	0.16	± 0.16	0.16	± 0.05		
S3	0.17	± 0.05	NA	NA	0.17	± 0.17	0.17	± 0.05	0.01	± 0.005
S4	8.0	± 0.4	4.1	± 0.2	3.9	± 0.4	NA	NA		

Abbreviations of the alternatives are defined in Table 3 of the main text. Non-common abbreviations: hh: household; GHG: greenhouse gas; NA: not analysed.

FIGURES

System analysis of material flows: results of modelling the MES

Analysed alternatives are defined in Table 2 of the main text.

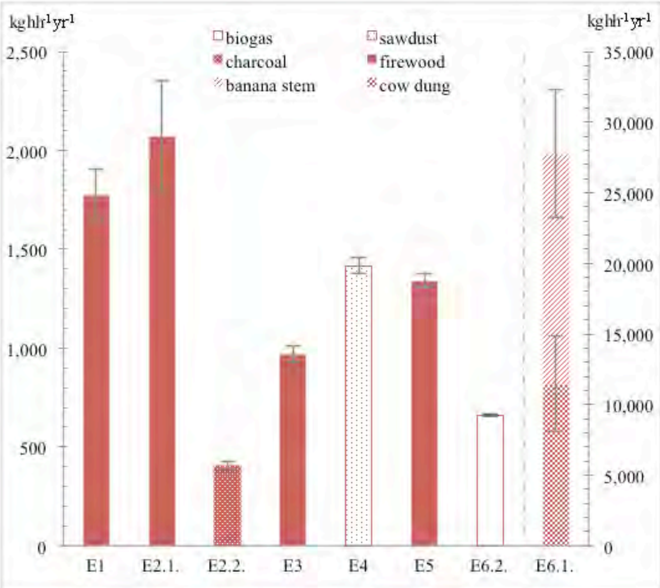

Fig. S.1: Material input flows of consumed resources, i.e. fuel required to fulfil the defined cooking task.
Results are expressed on the goods layer in kg of fresh matter per household and year; abbreviations of the alternatives are defined in Table 2 of the main text; alternative E6.1. refers to the right-hand ordinate; plot data provided in Table 4 of the main text.

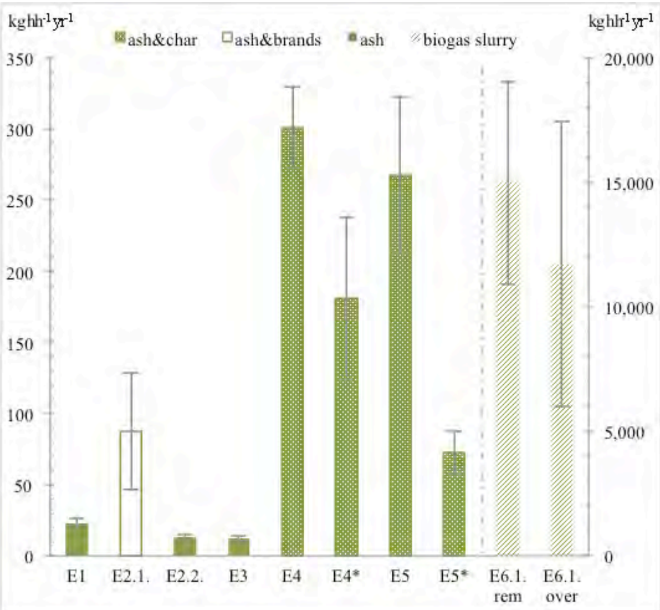

Fig. S.2: Material output flows of residues available after performing the defined cooking task and for potential recycling to the agroecosystem.
Results are expressed for the goods layer in in kg of fresh matter per household and year; abbreviations of the alternatives are defined in Table 2 of the main text; alternative E6.1. refers to the right-hand ordinate; plot data provided in Table 4

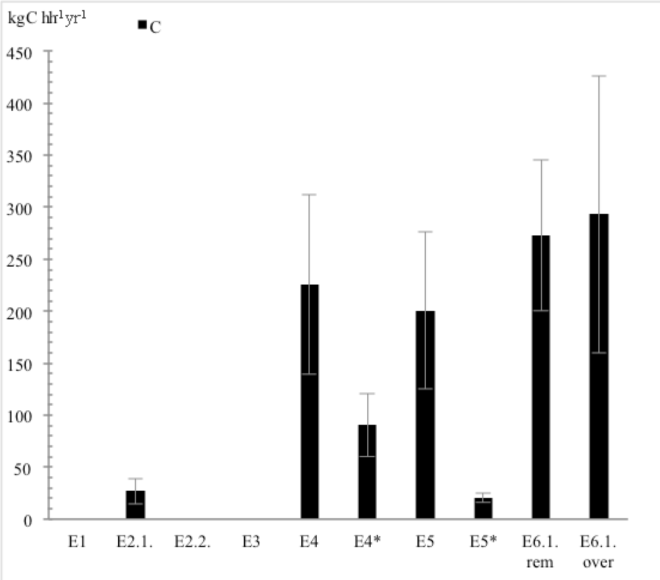

Fig. S.3: The C recovery, i.e. C content in material output flows of residues.
Results are expressed in kg of C per household and year; abbreviations of the alternatives are defined in Table 2 of the main text; plot data in Table 4 of the main text.

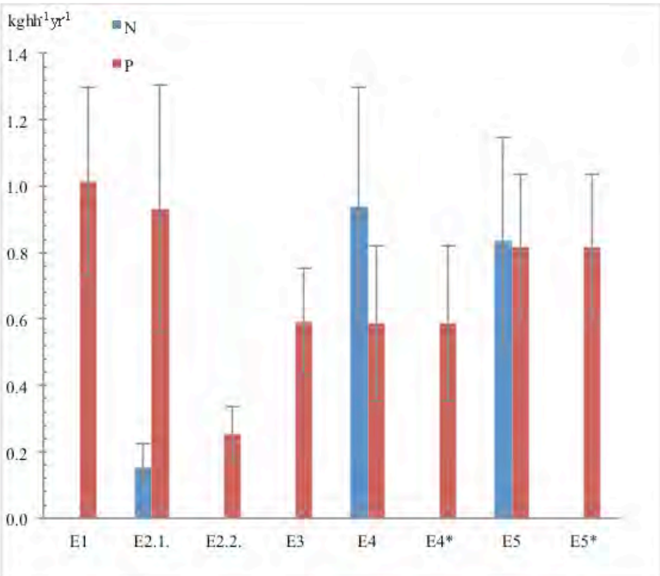

Fig. S.4: The nutrient recycling potential, i.e. content of N (blue bars) and P (red bars) in material output flows of residues.
Results are expressed in kg of P and kg of N per household and year; abbreviations of the alternatives are defined in Table 2 of the main text; plot data in Table 4 of the main text.

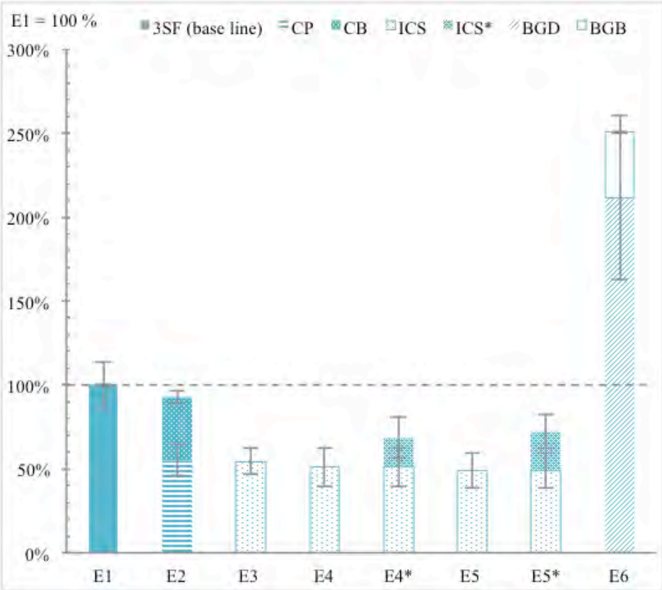

Fig. S.5: Relative material output flows of greenhouse gas (GHG) emissions of the analysed bioenergy alternatives compared to the current state of using a three-stone fire (E1=100 %);

The GHG-emissions were assessed with global warming potential (GWP) as provided by Myhre (2013); selected GWP-factors are presented in Table A.6; abbreviations of the alternatives are defined in Table 2 of the main text; ultimate data for GHG-emissions are provided in Table S.7.

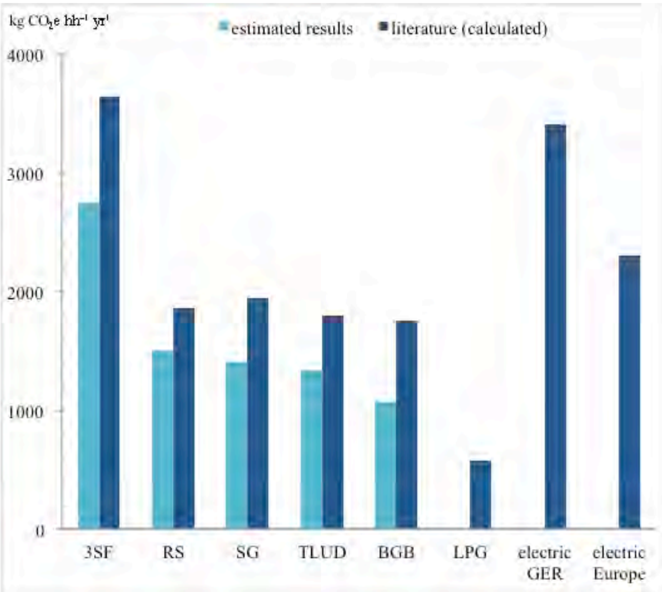

Fig. S.6: Plausibility check by comparing the estimated GHG emissions from cooking with literature [Smith et al. (2000) for 3SF, RS, SG, TLUD, BGB and LPG and Atlantic consulting (2009) for electricity in Germany and Europe].

Figures are expressed in kg CO2-equivalents per household and year; selected GWP-factors are presented in Table A.6; abbreviations of the alternatives are defined in Table 2 of the main text; plot data in Table S.9.

System analysis of material flows: results modelling the MSS

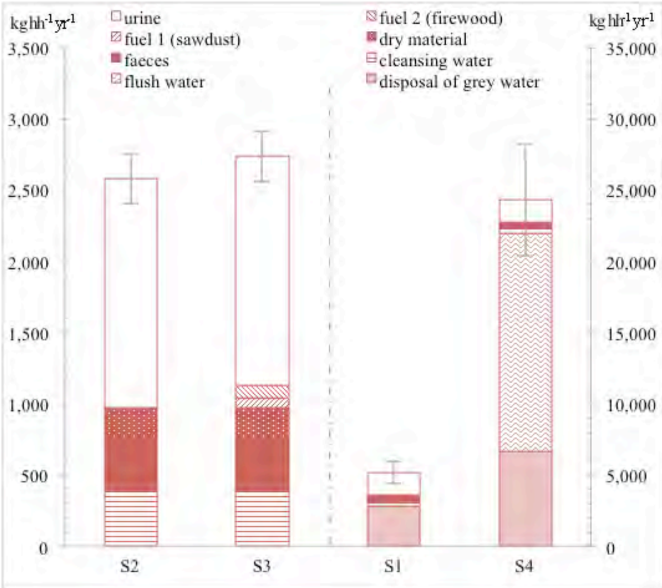

Fig. S.7: Material input flows of resources, i.e. total load of material to the sanitation facilities.
Results are expressed in kg of fresh matter per household and year; abbreviations of the alternatives are defined in Table 3 of the main text; alternatives S1 and S4 refer to the right-hand ordinate; plot data provided in Table S.10.

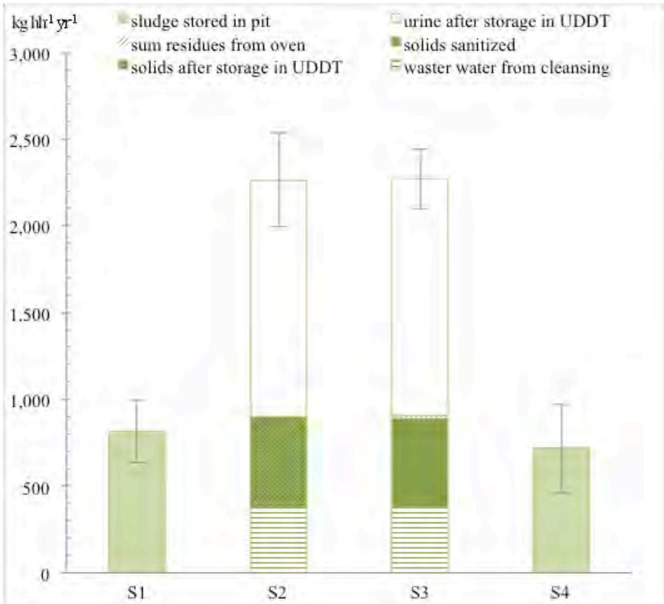

Fig. S.8: Material output flows of residues available from sanitation facilities; residues from EcoSan (S2, S3) are potentially available for recycling to the agroecosystem; residues from conventional systems (S1, S4) are stored in the pit.
Results are expressed in kg of fresh matter per household and year; abbreviations of the alternatives are defined in Table 2 of the main text; plot data provided in Table 5 of the main text.

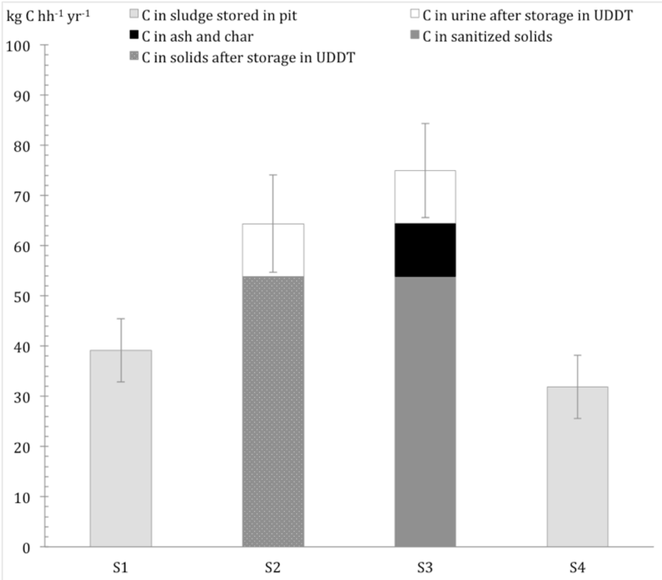

Fig. S.9: The C recovery, i.e. C content in material output flows of residues.
Results are expressed in kg of C per household and year; abbreviations of the alternatives are defined in Table 3 of the main text; plot data in Table S.11.

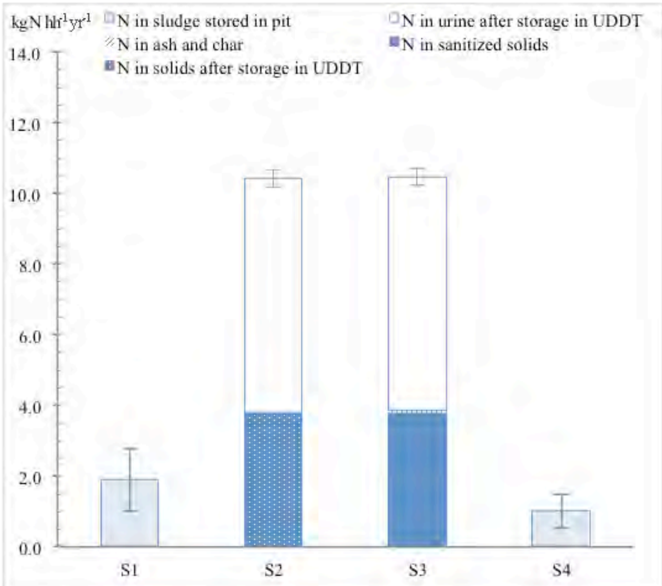

Fig. S.10: The N-recycling potential, i.e. content of N in material output flows of residues.
Results are expressed in kg of N per household and year; abbreviations of the alternatives are defined in Table 3 of the main text; plot data in Table S.12.

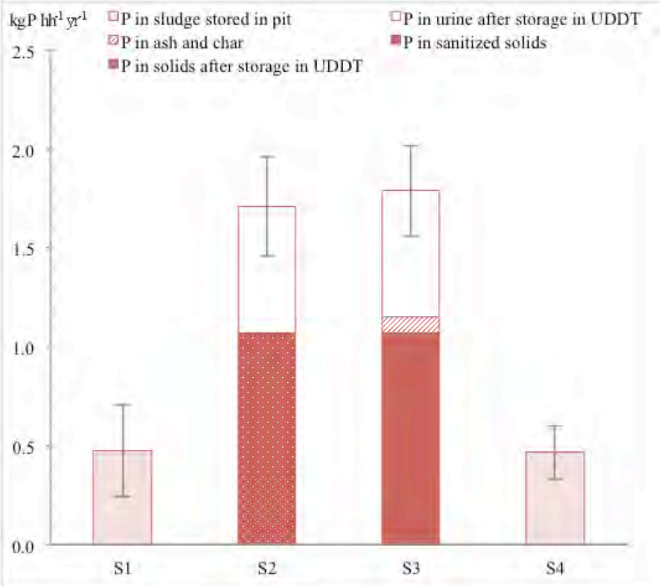

Fig. S.11: The P-recycling potential, i.e. content of P in material output flows of residues.
Results are expressed in kg of P per household and year; abbreviations of the alternatives are defined in Table 3 of the main text; plot data in Table S.13.

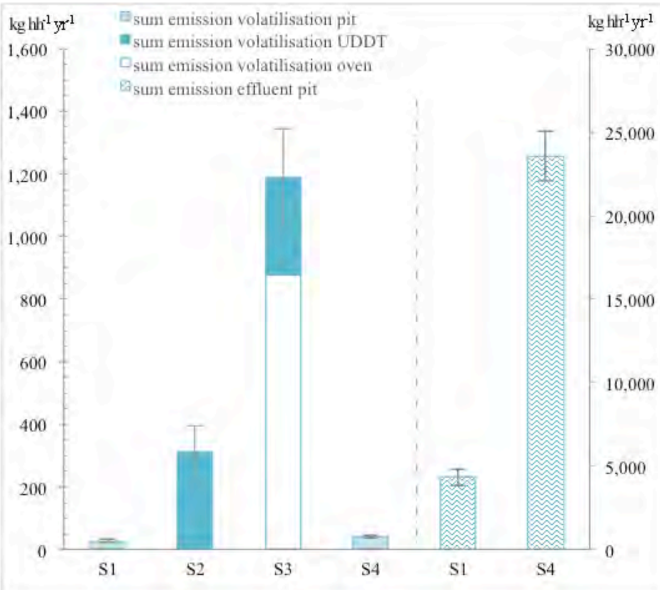

Fig. S.12: Total emissions from the sanitation system, i.e. gaseous emissions from volatilisation (left-hand ordinate) and liquid emissions through effluents (right-hand ordinate).
Results are expressed in kg of fresh matter per household and year; abbreviations of the alternatives are defined in Table 3 of the main text; plot data in Table S.16 (gaseous emissions) and S.15 (liquid emissions).

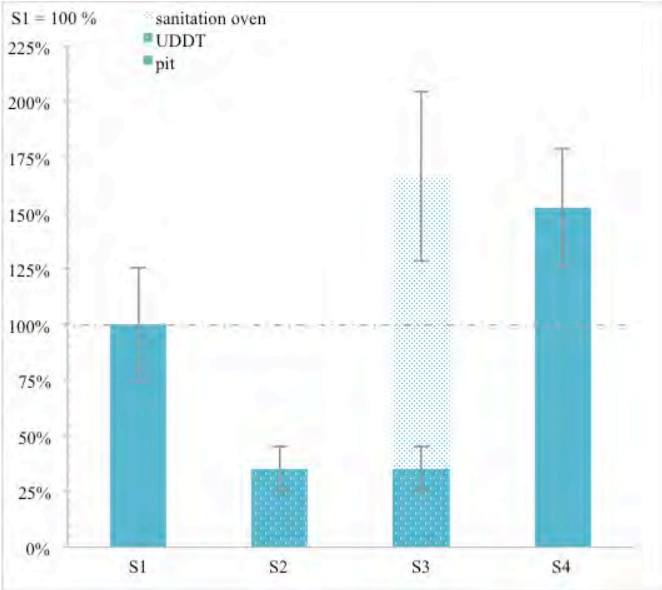

Fig. S.13: Relative material output flows of greenhouse gas (GHG) emissions from EcoSan (S2, S3) and from water-based (S4) sanitation facilities compared to current state of using a pit latrine (S1=100 %).
GHG-emissions were assessed with global warming potential (GWP) as provided by Myhre (2013); selected GWP-factors as shown in Table B.5; ; abbreviations of the alternatives are defined in Table 3 of the main text; plot data provided in Table S.17.

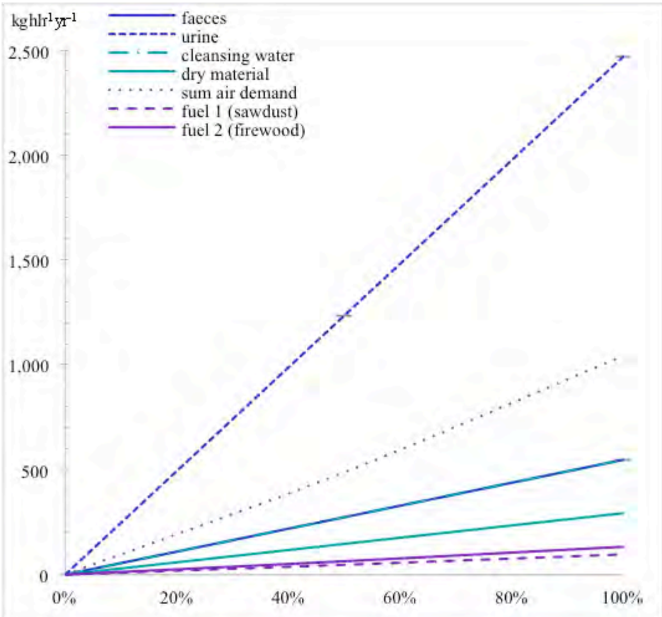

Fig. S.14: Linear interpolation of material input flows to the UDDT (ordinate) in relation to the average daily usage of the UDDT by the household members (abscissa).
Results are expressed in kg of fresh matter per household and year for the material input and in % for the toilet usage; non-common abbreviations: UDDT: urine-diverting dry toilet.

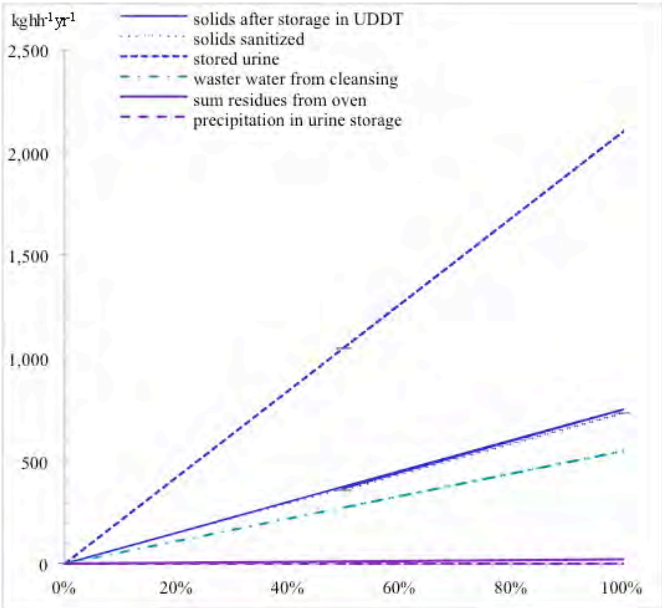

Fig. S.15: Linear interpolation of material output flows from the UDDT (ordinate) in relation to the average daily usage of the UDDT by the household members (abscissa).

Results are expressed in kg of fresh matter per household and year for the material input and in % for the toilet usage; non-common abbreviations: UDDT: urine-diverting dry toilet.

System analysis of material flows: results of modelling the MES

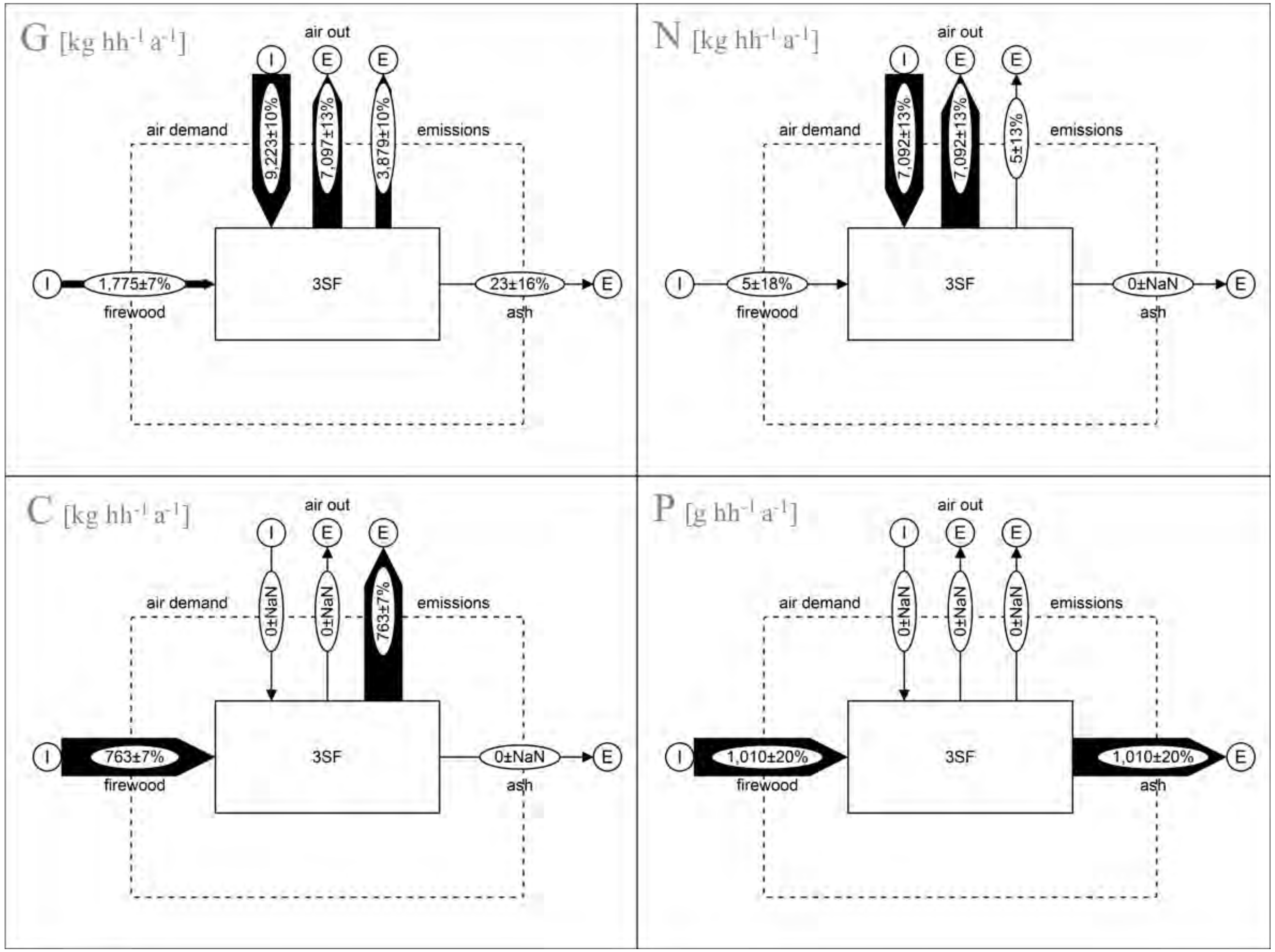

Fig. S.16: Flow diagrams of the bioenergy alternative E1, the three-stone-fire (3SF), for the layer of goods (G) and indicator elements C, N, P in kg per household per year.
Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

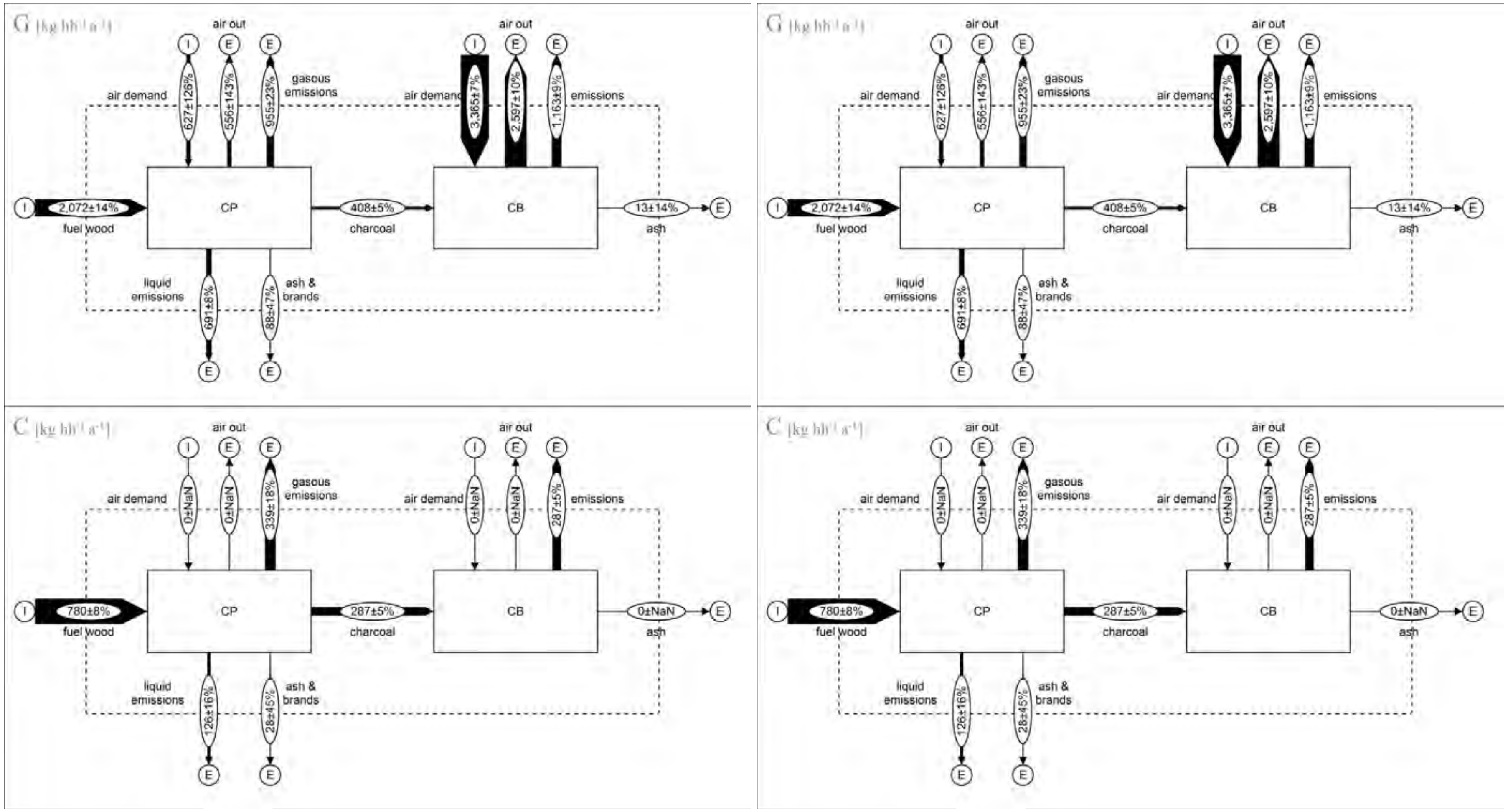

Fig. S.17: Flow diagrams of the bioenergy alternative E2, the charcoal system including charcoal production (CP) and charcoal burners (CB), for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

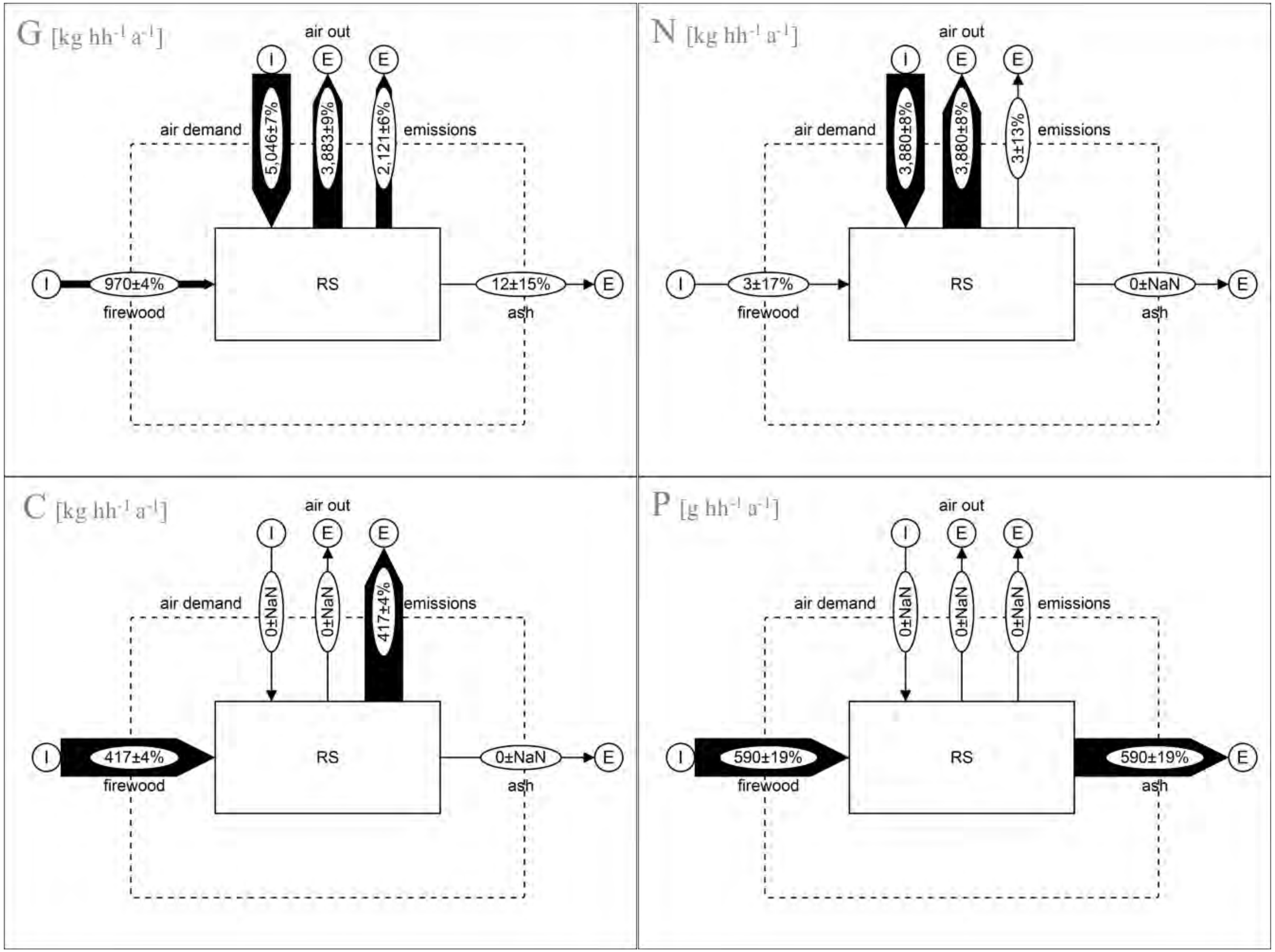

Fig. S.18: Flow diagrams of the bioenergy alternative E3, the rocket stove (RS), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

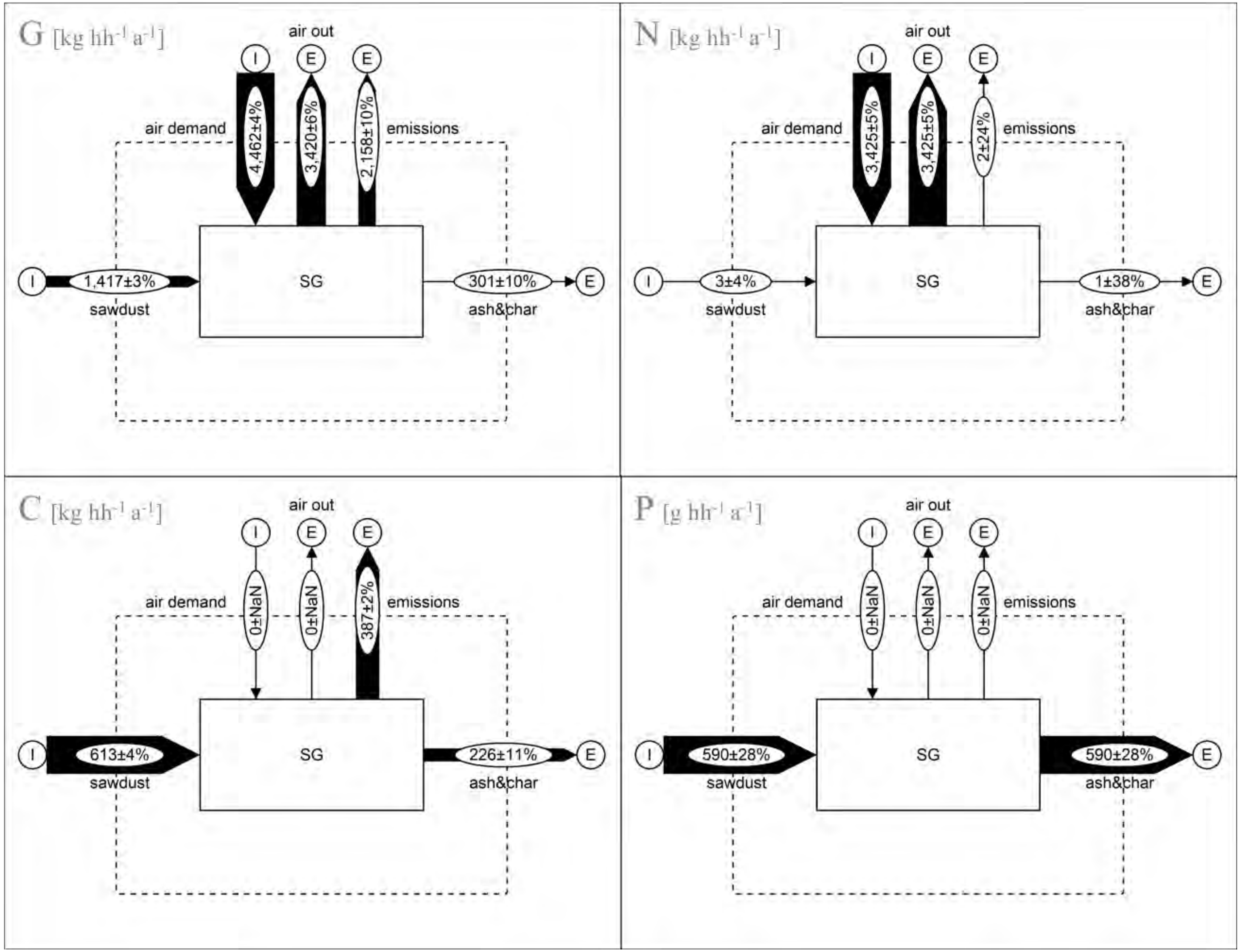

Fig. S.19: Flow diagrams of the bioenergy alternative E4, the sawdust gasifier (SG), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

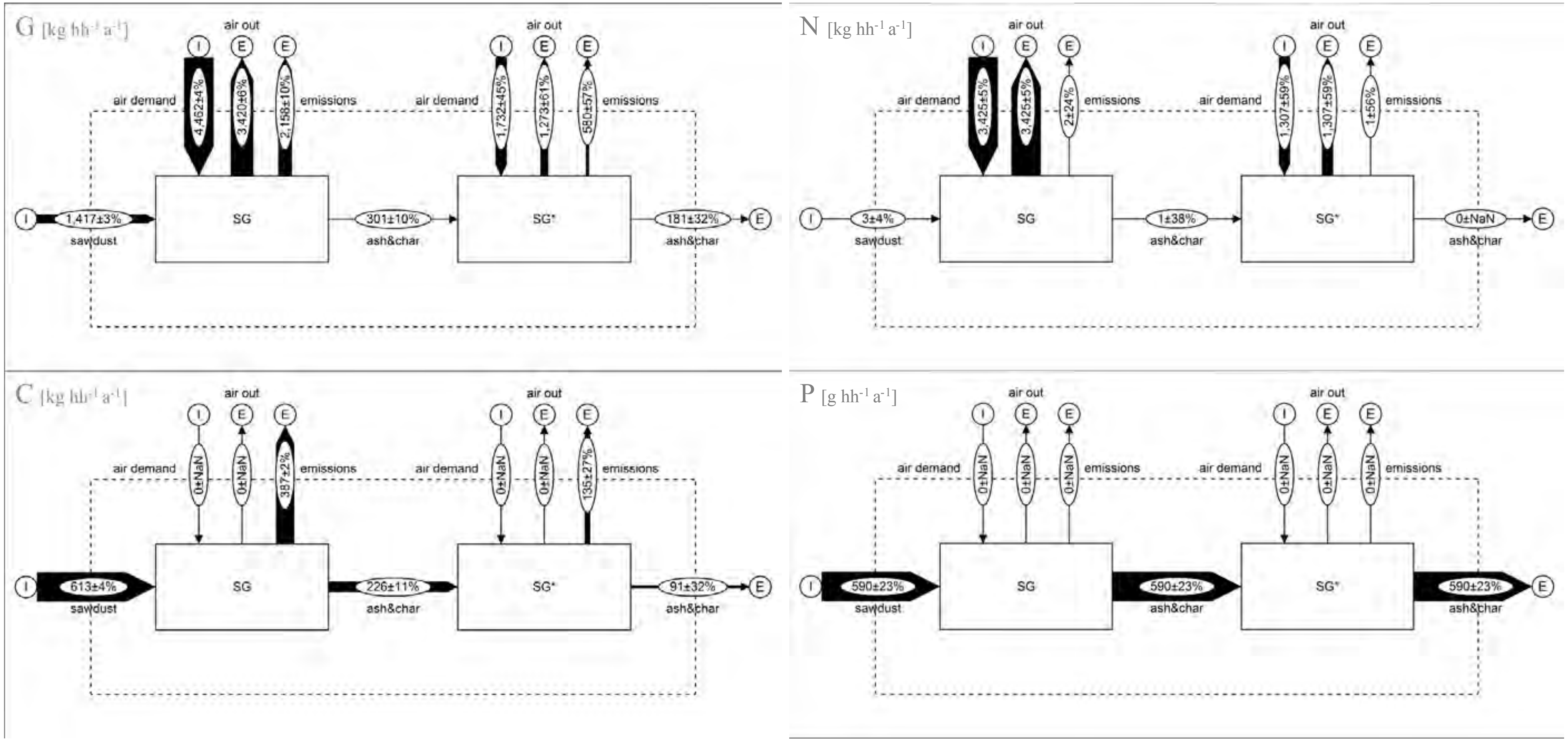

Fig. S.20: Flow diagrams of the bioenergy alternative E4*, the sawdust gasifier * next morning (SG*), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

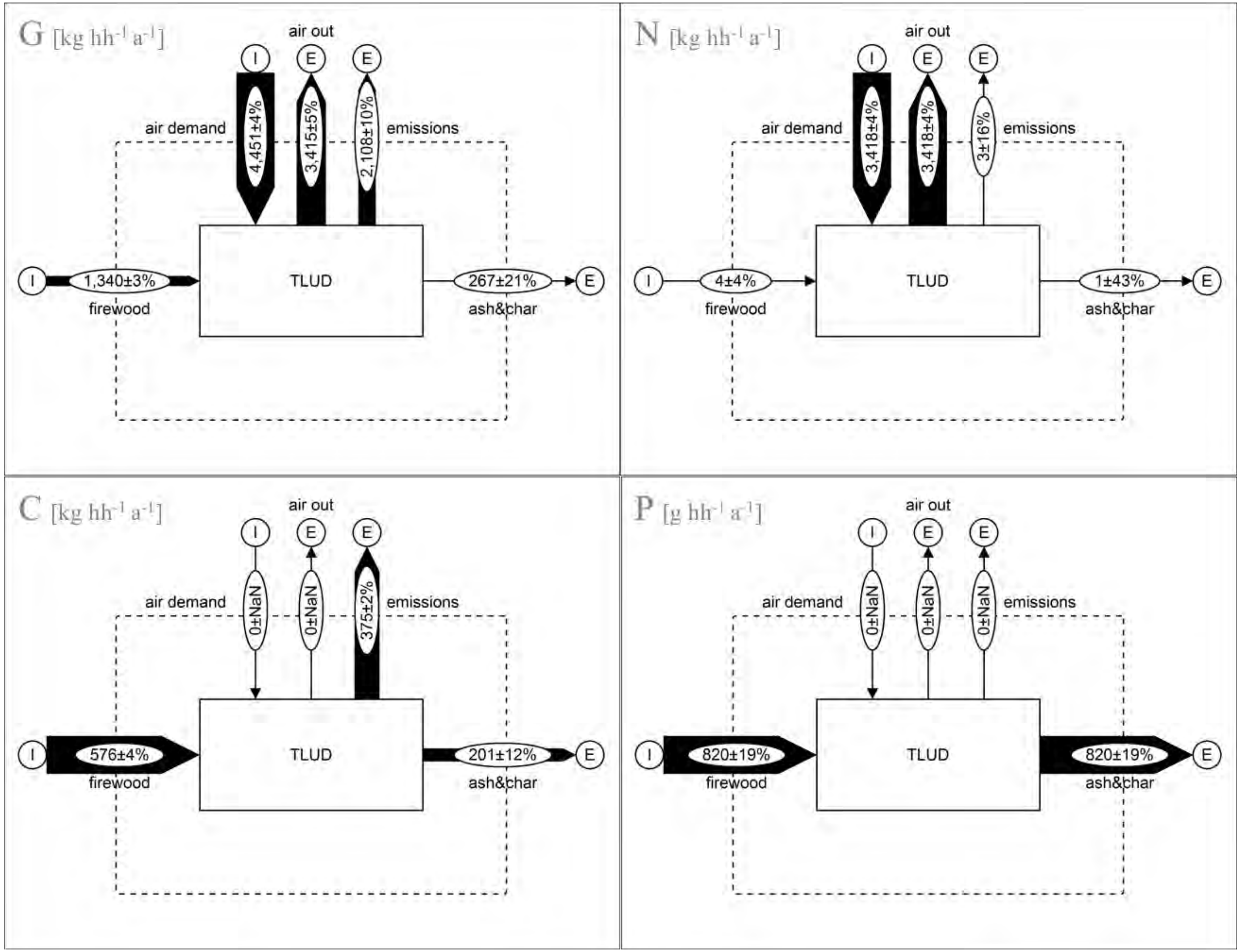

Fig. S.21: Flow diagrams of the bioenergy alternative E5, the Top-Lit UpDraft gasifier (TLUD), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

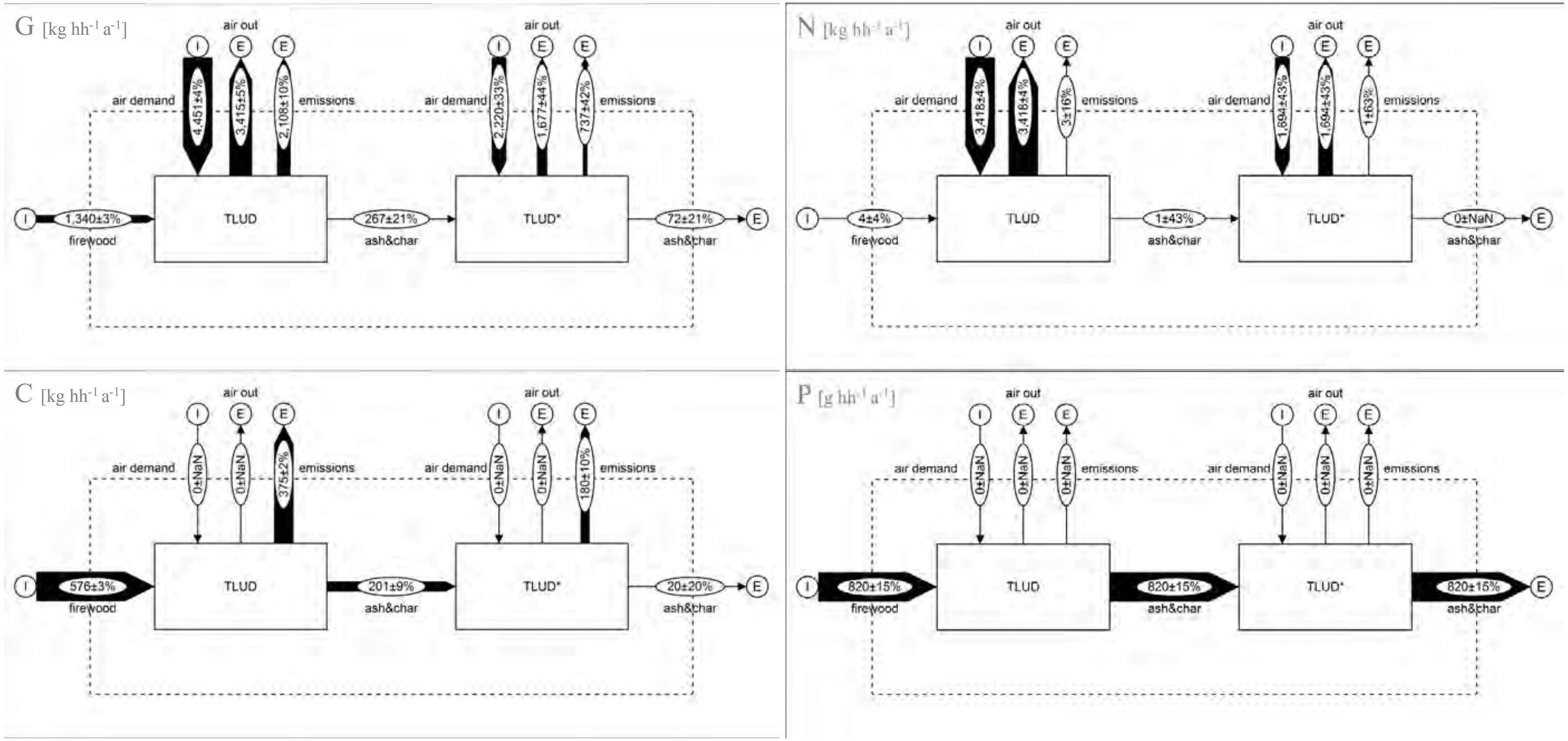

Fig. S.22: Flow diagrams of the bioenergy alternative E5*, the Top-Lit UpDraft gasifier * next morning (TLUD*), for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

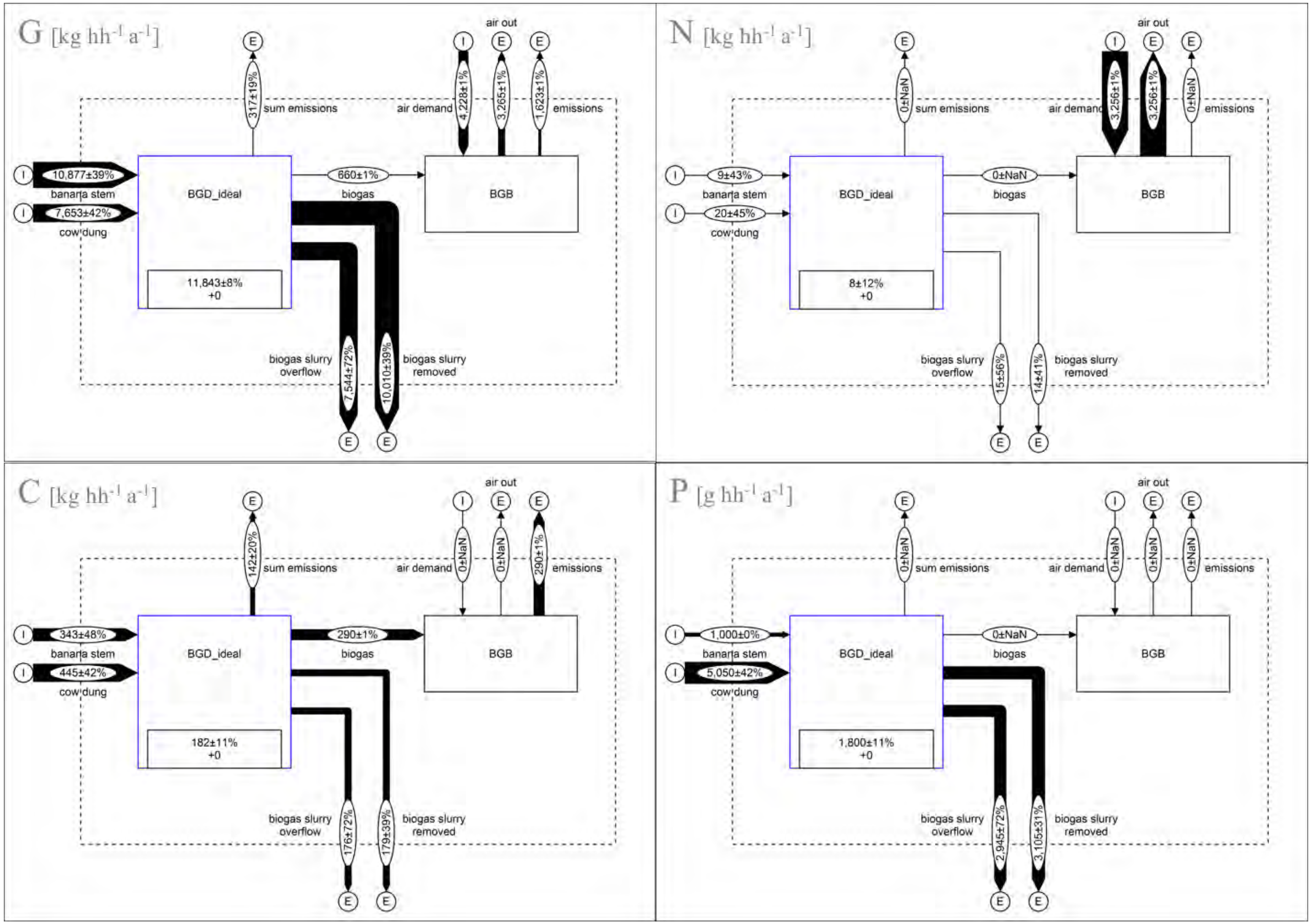

Fig. S.23: Flow diagrams of the bioenergy alternative E6, the biogas system including biogas digester (BGD) and biogas burner (BGB) in the 'ideal world' model and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

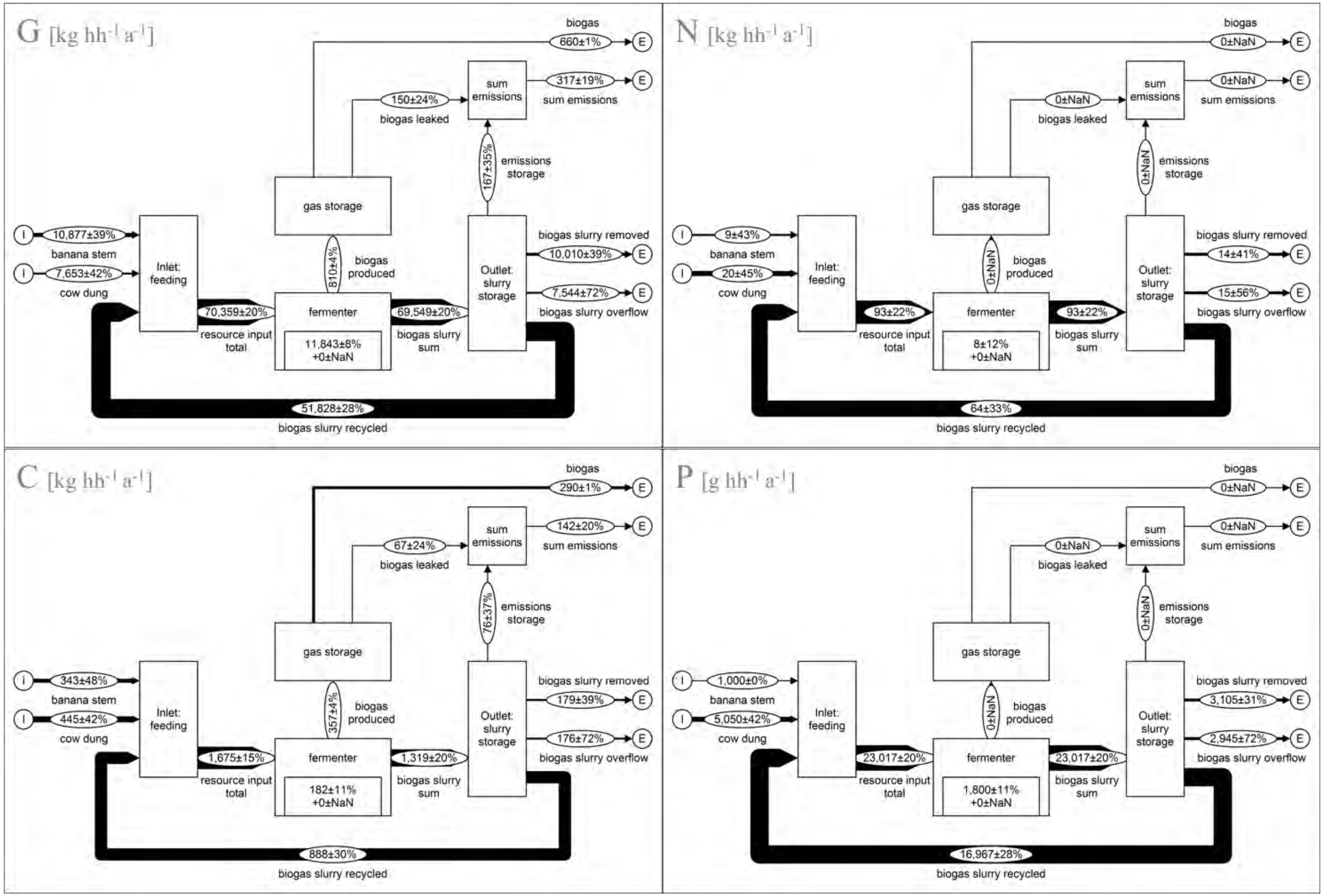

Fig. S.24: Flow diagrams of the sub-process ‘biogas digester’ analysed in bioenergy alternative E6, in the ‘ideal world’ model and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

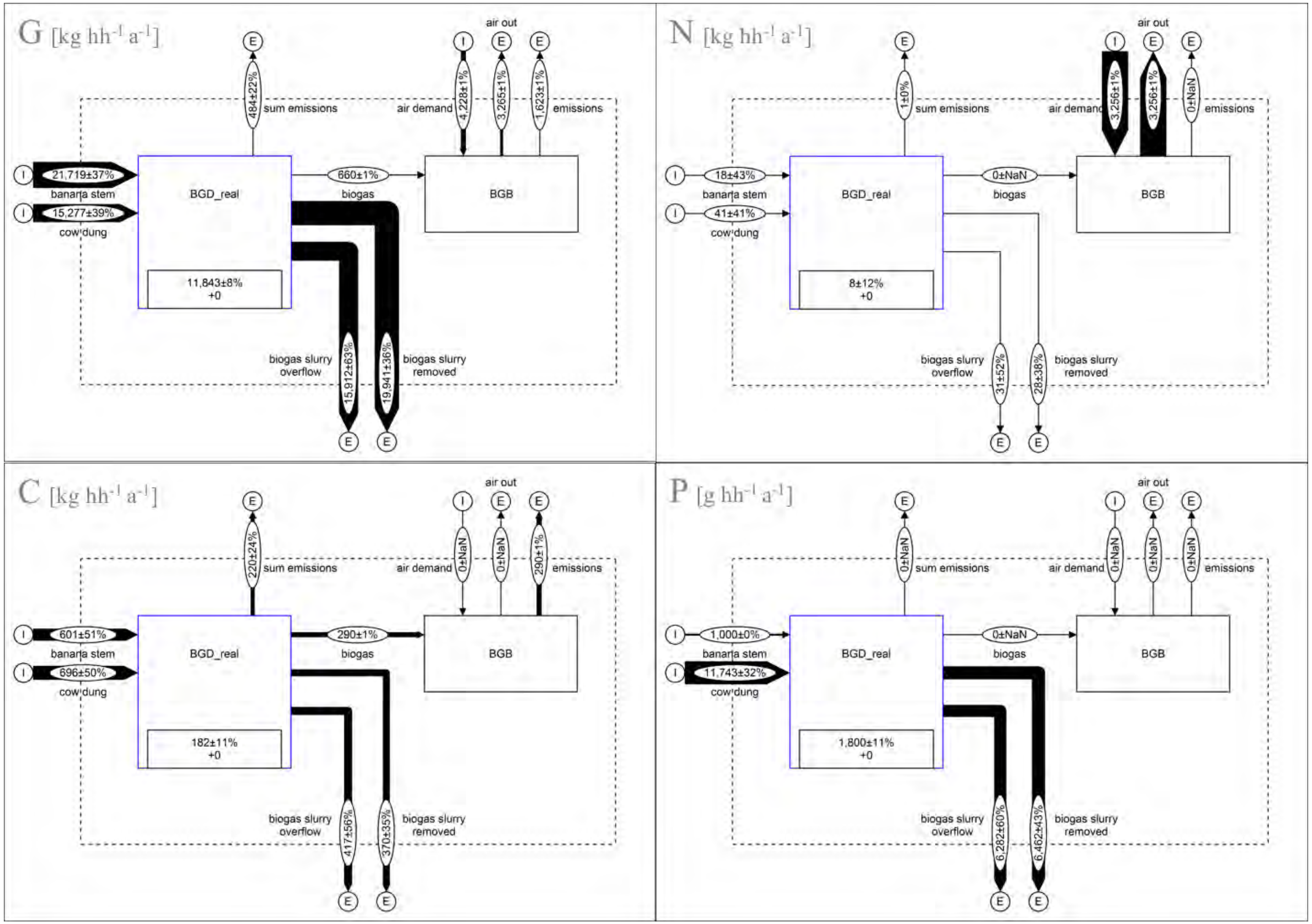

Fig. S.25: Flow diagrams of the bioenergy alternative E6, the biogas system including biogas digester (BGD) and biogas burner (BGB) in the ‘real world’ model and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

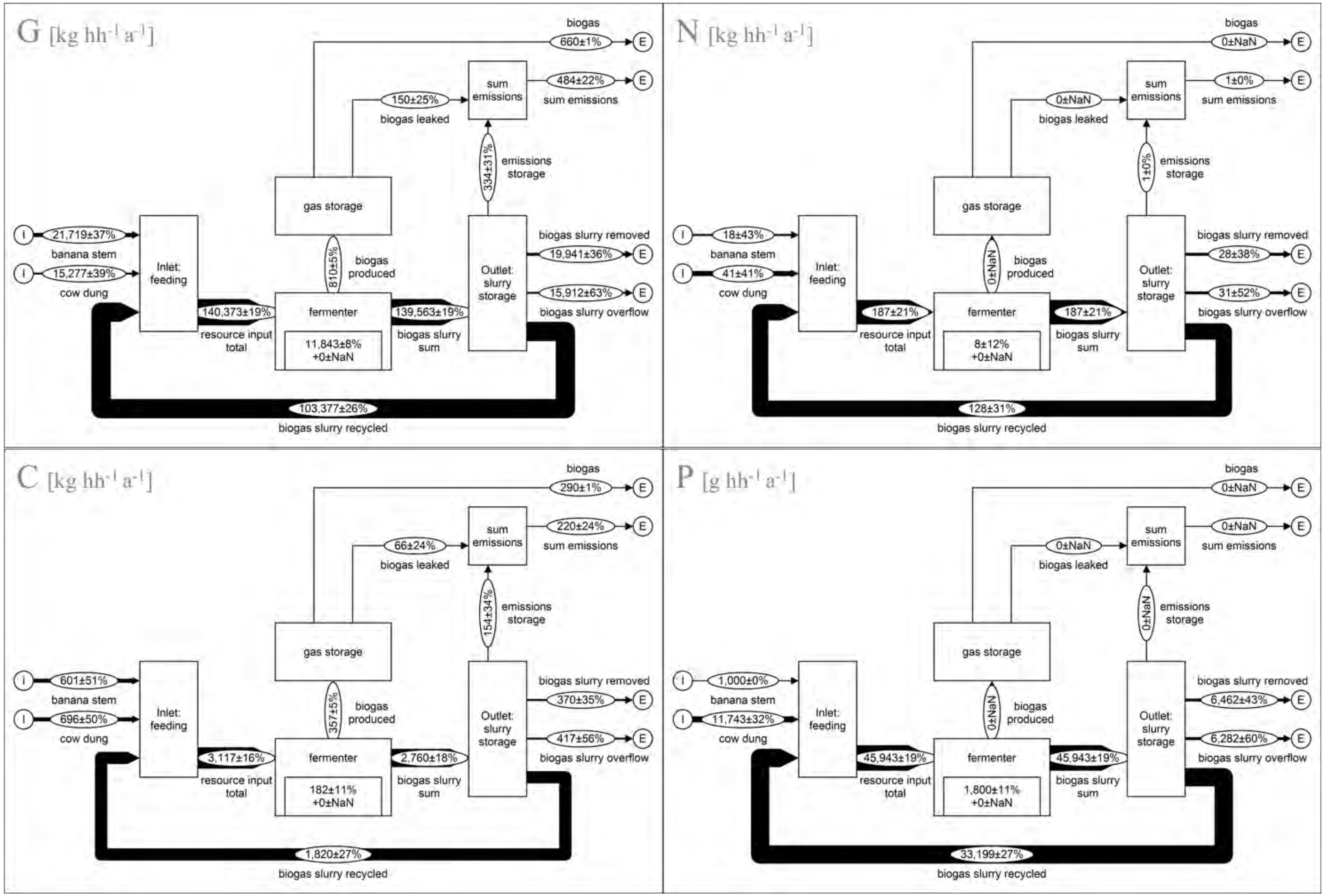

Fig. S.26: Flow diagrams of the sub-process 'biogas digester' analysed in bioenergy alternative E6, in the 'real world' model and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

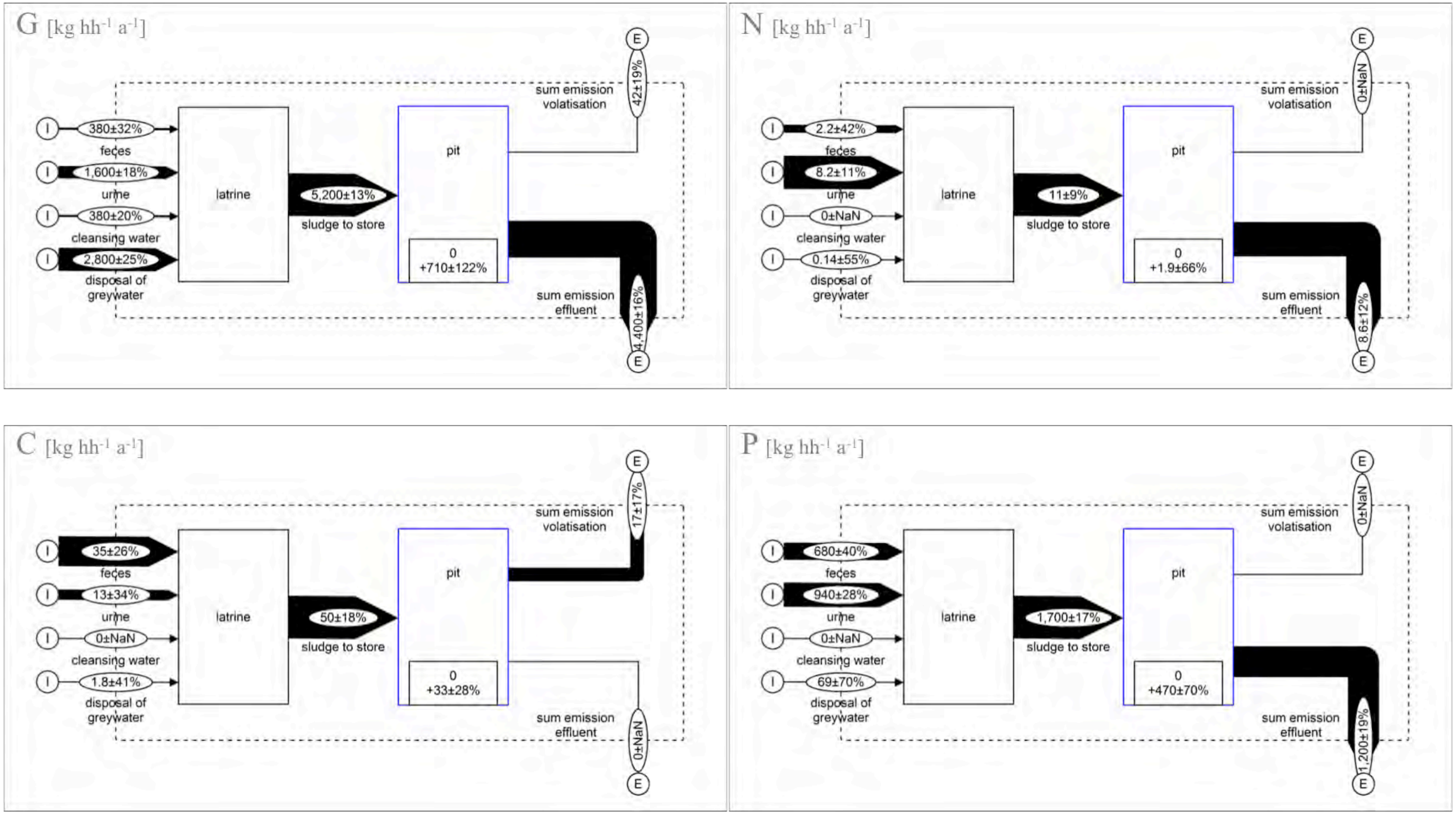

Fig. S.27: Flow diagrams of the sanitation alternative S1, the pit latrine, exemplarily shown for the variance S1_1 (see Table B.4) and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

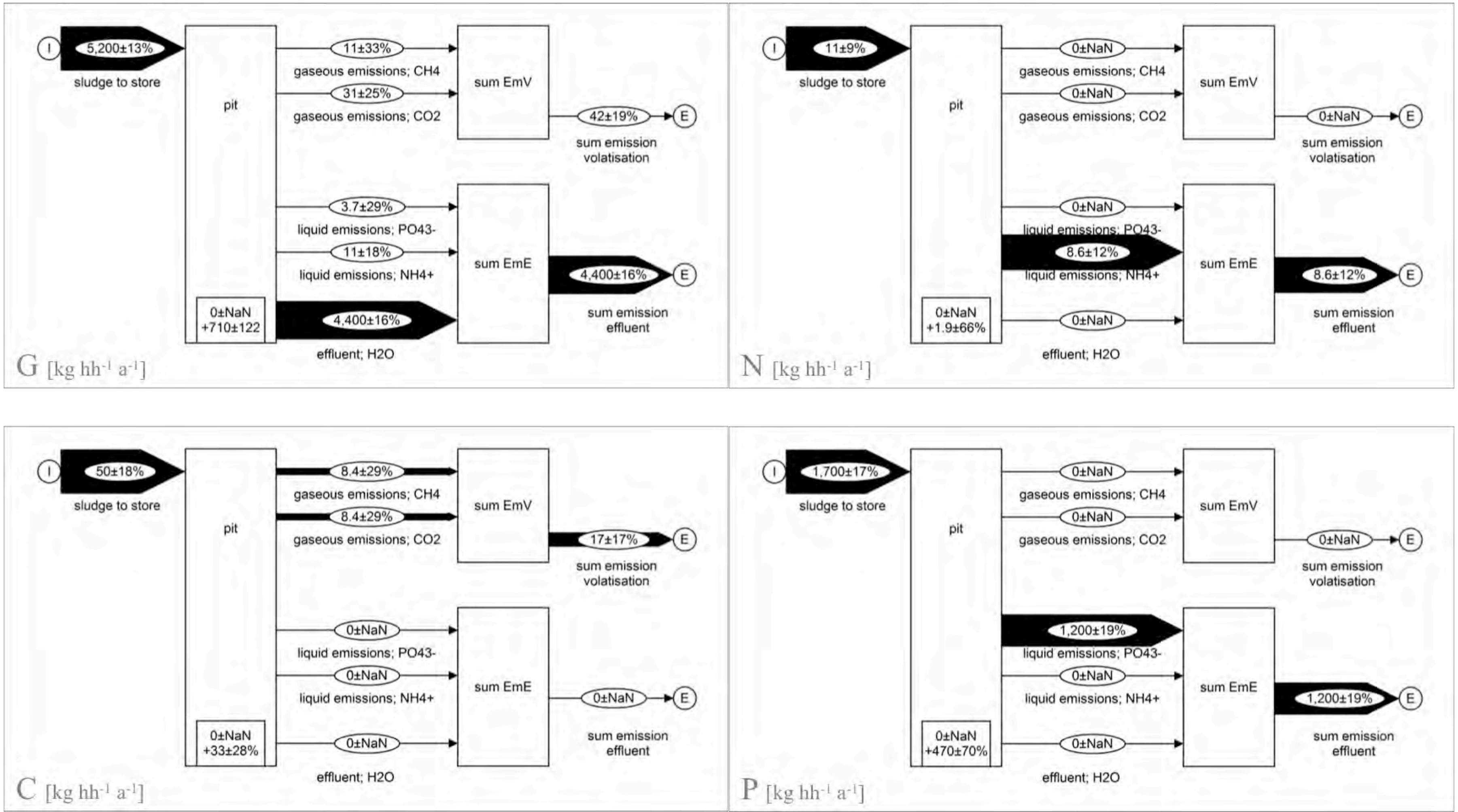

Fig. S.28: Flow diagrams of the sub-process ‘pit’ analysed in sanitation alternative S1, exemplarily shown for the variance S1_1 (see Table B.4) and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

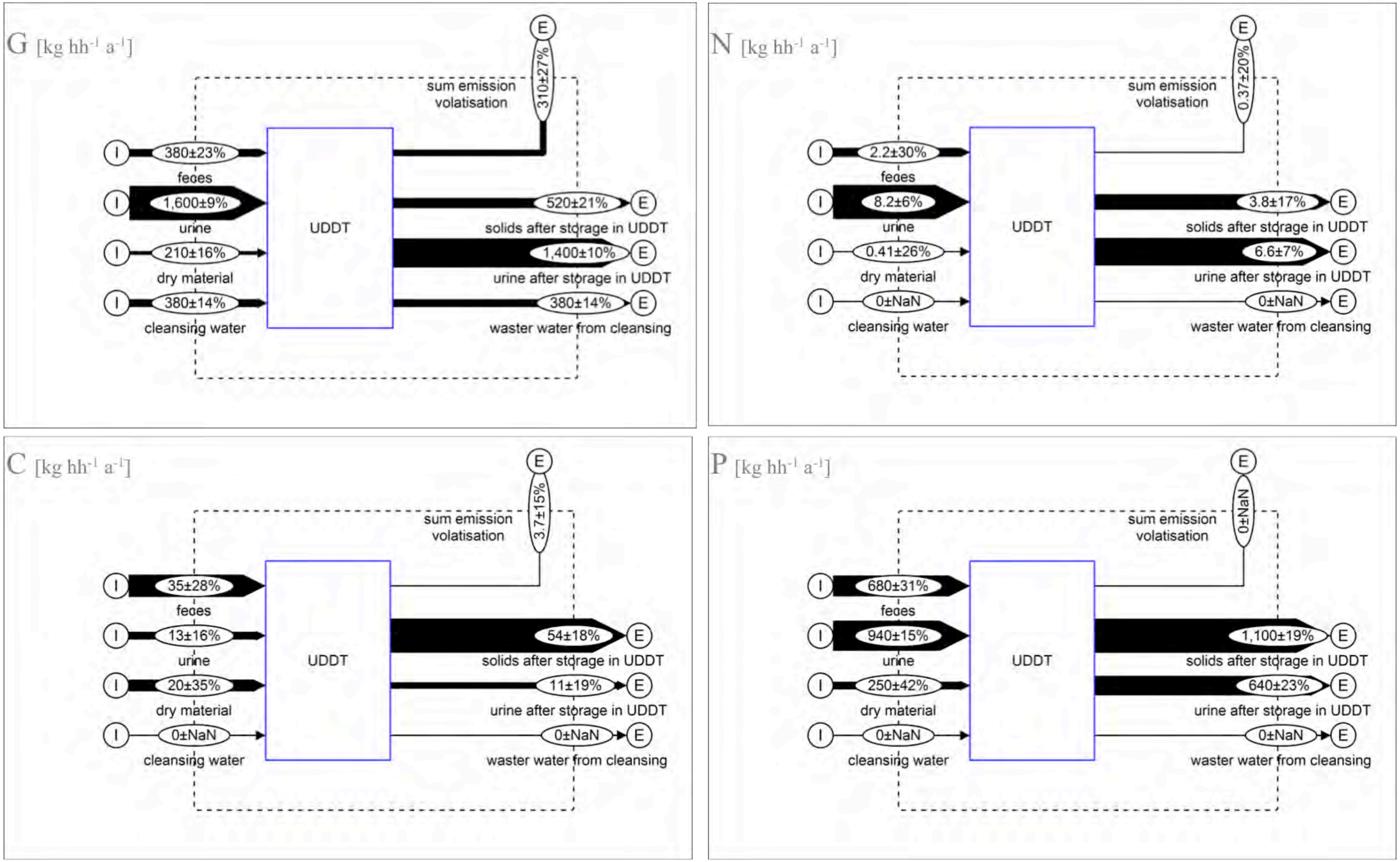

Fig. S.29: Flow diagrams of the sanitation alternative S2, the urine-diverting dry toilet (UDDT), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

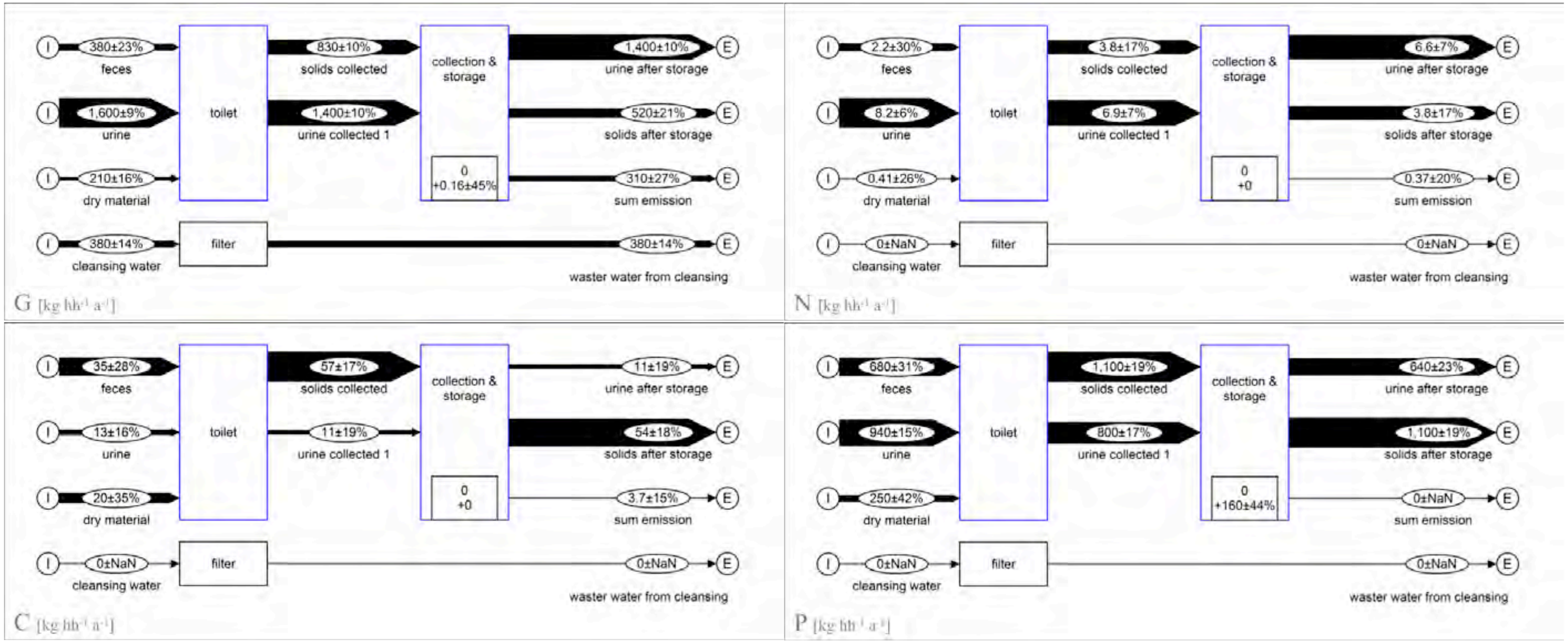

Fig. S.30: Flow diagrams of the sub-process 'UDDT' analysed in sanitation alternative S2, for the layer of goods (G) and indicator elements C, N, P in kg per household per year.
Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

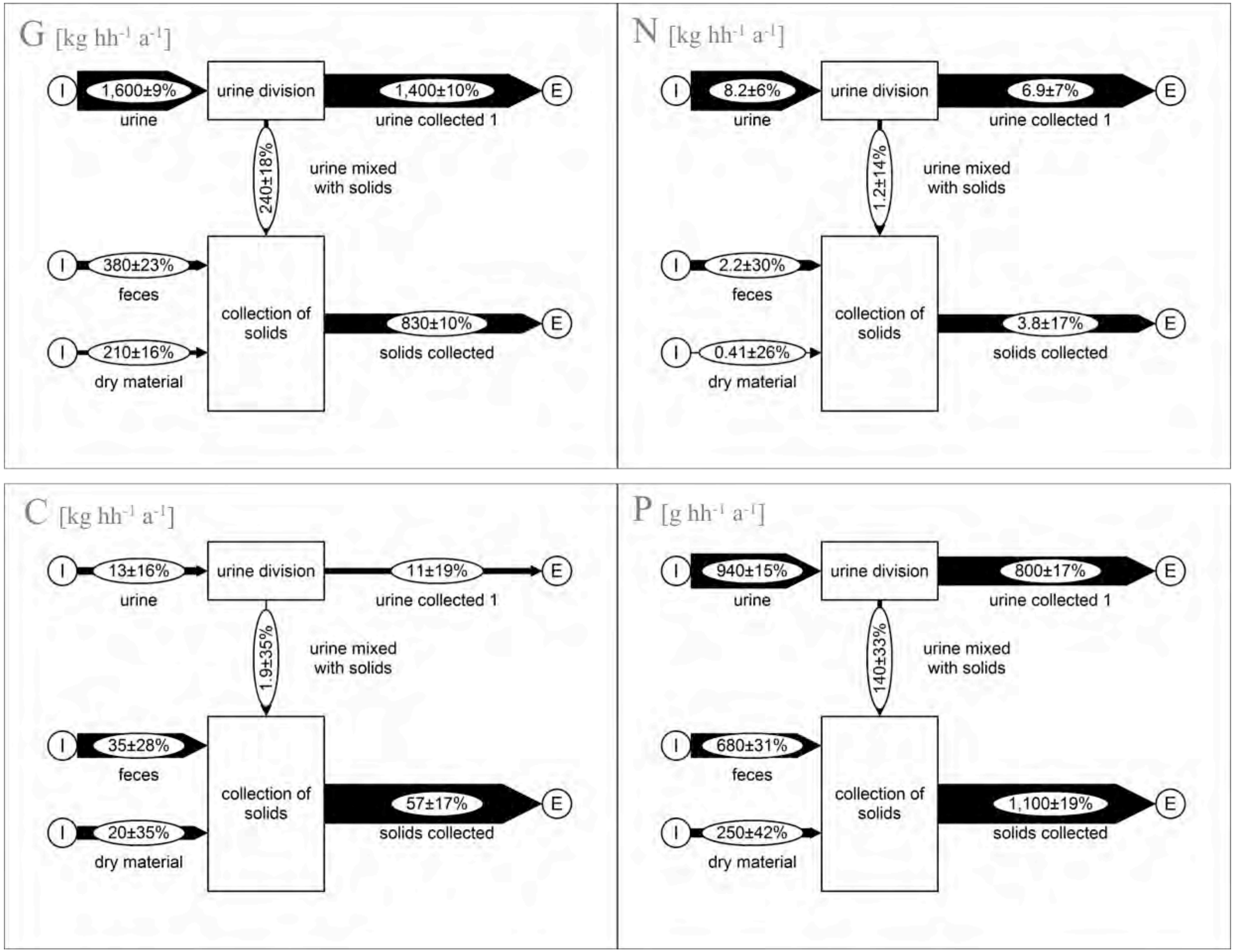

Fig. S.31: Flow diagrams of the sub-process 'toilet' analysed in the sub-process UDDT of the sanitation alternative S2, for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

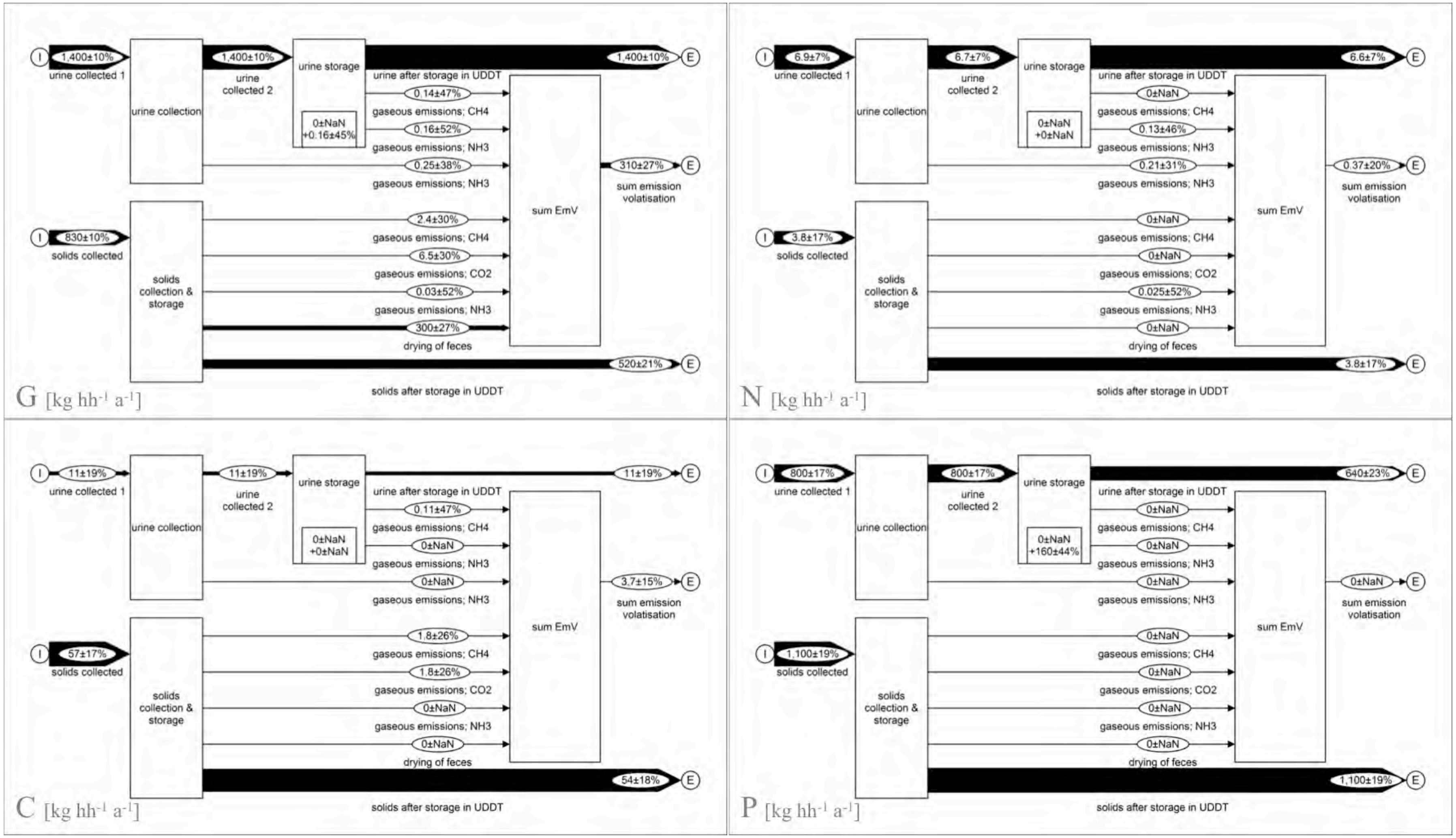

Fig. S.32: Flow diagrams of the sub-process 'collection & storage' analysed in the sub-process UDDT of the sanitation alternative S2, for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

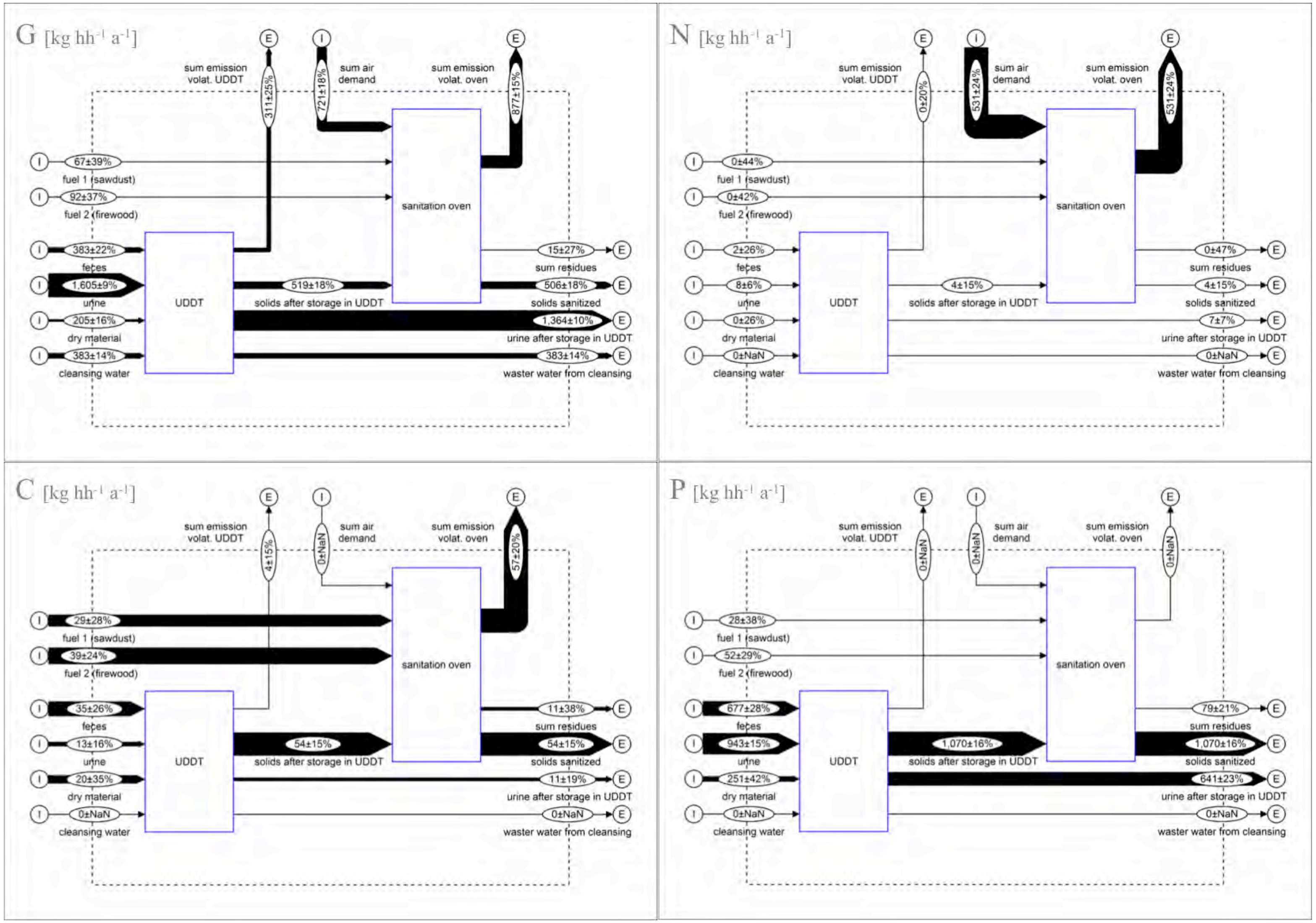

Fig. S.33: Flow diagrams of the sanitation alternative S3, the CaSa-concept including a urine-diverting dry toilet (UDDT) and a sanitation oven, for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

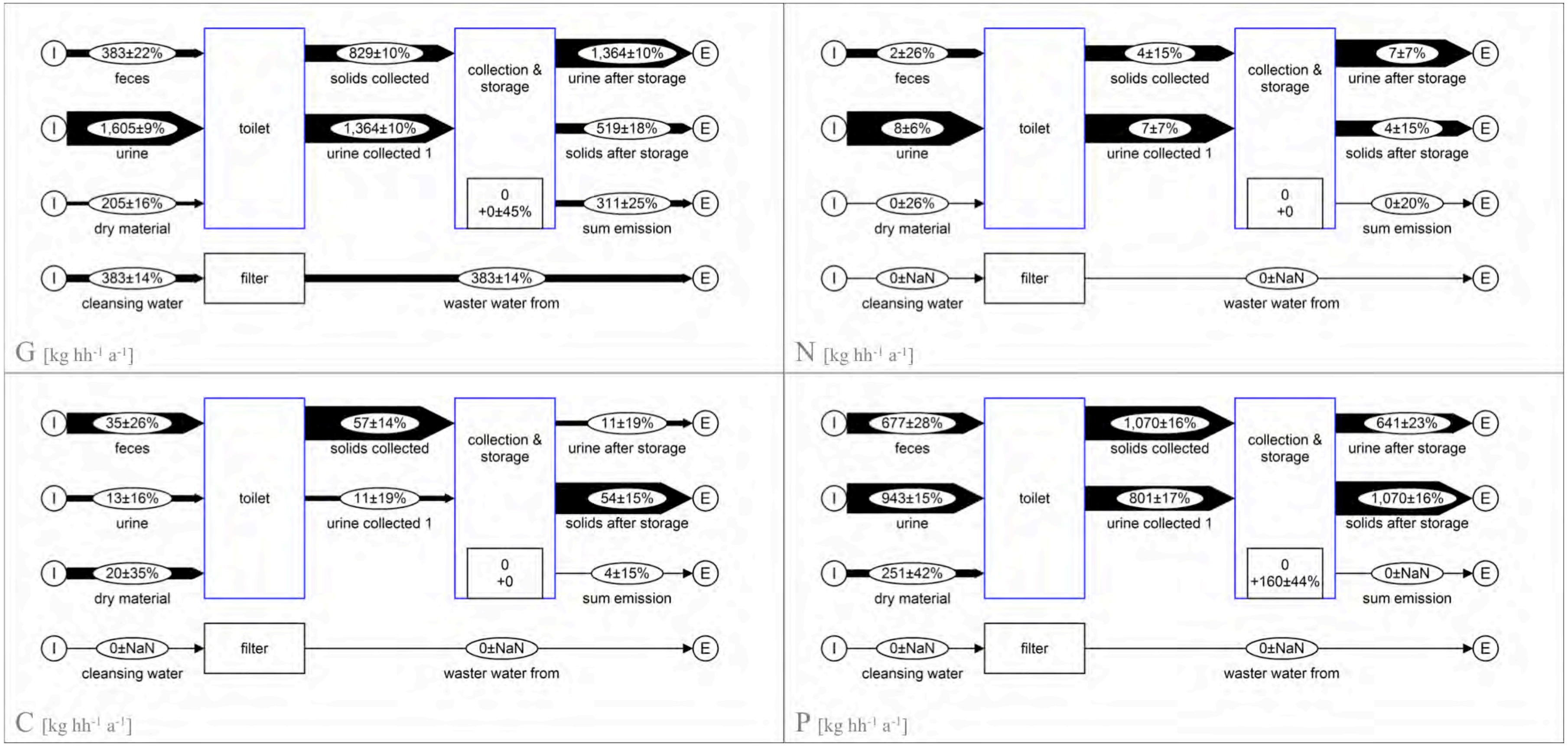

Fig. S.34: Flow diagrams of the sub-process 'UDDT' analysed in sanitation alternative S3, for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

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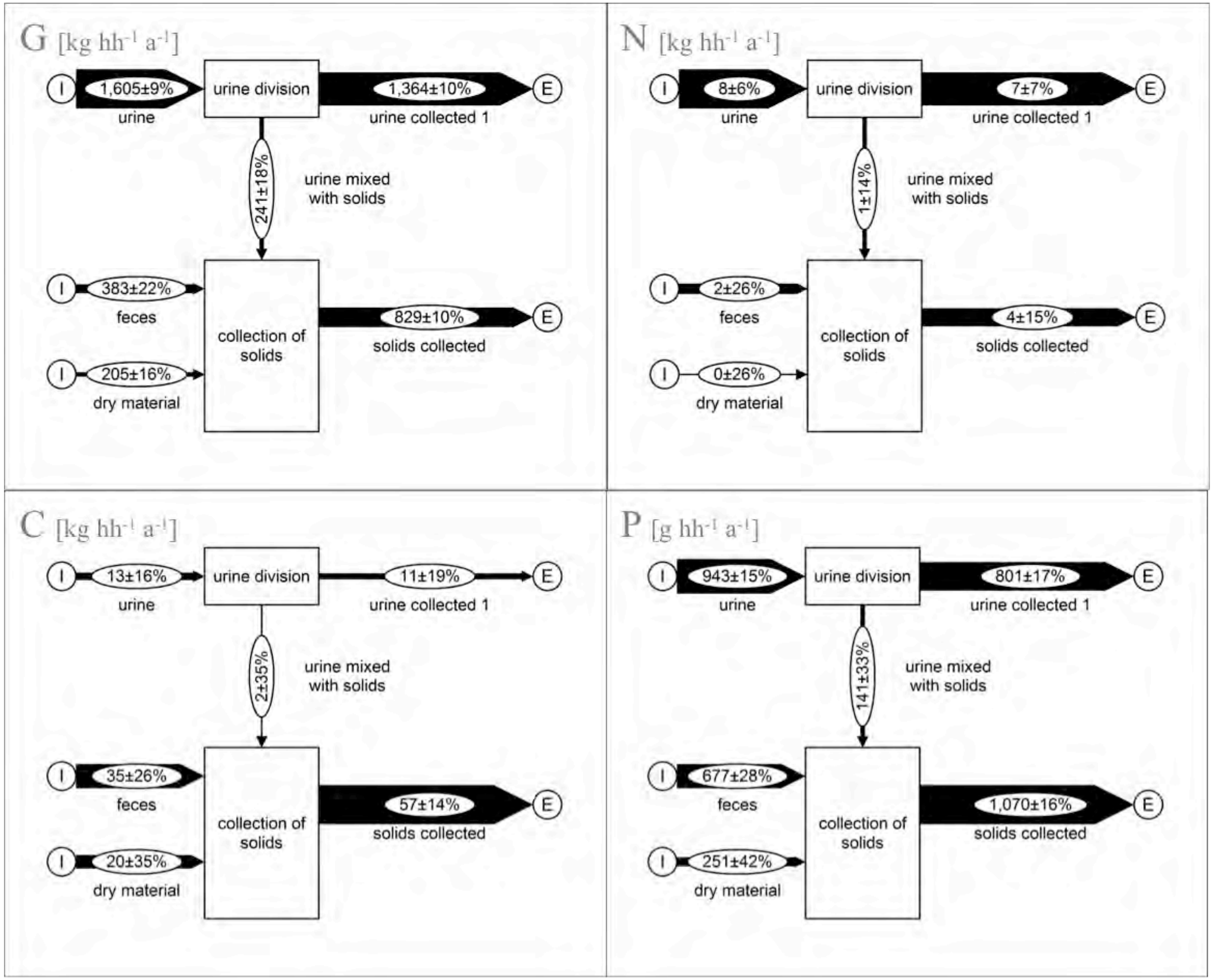
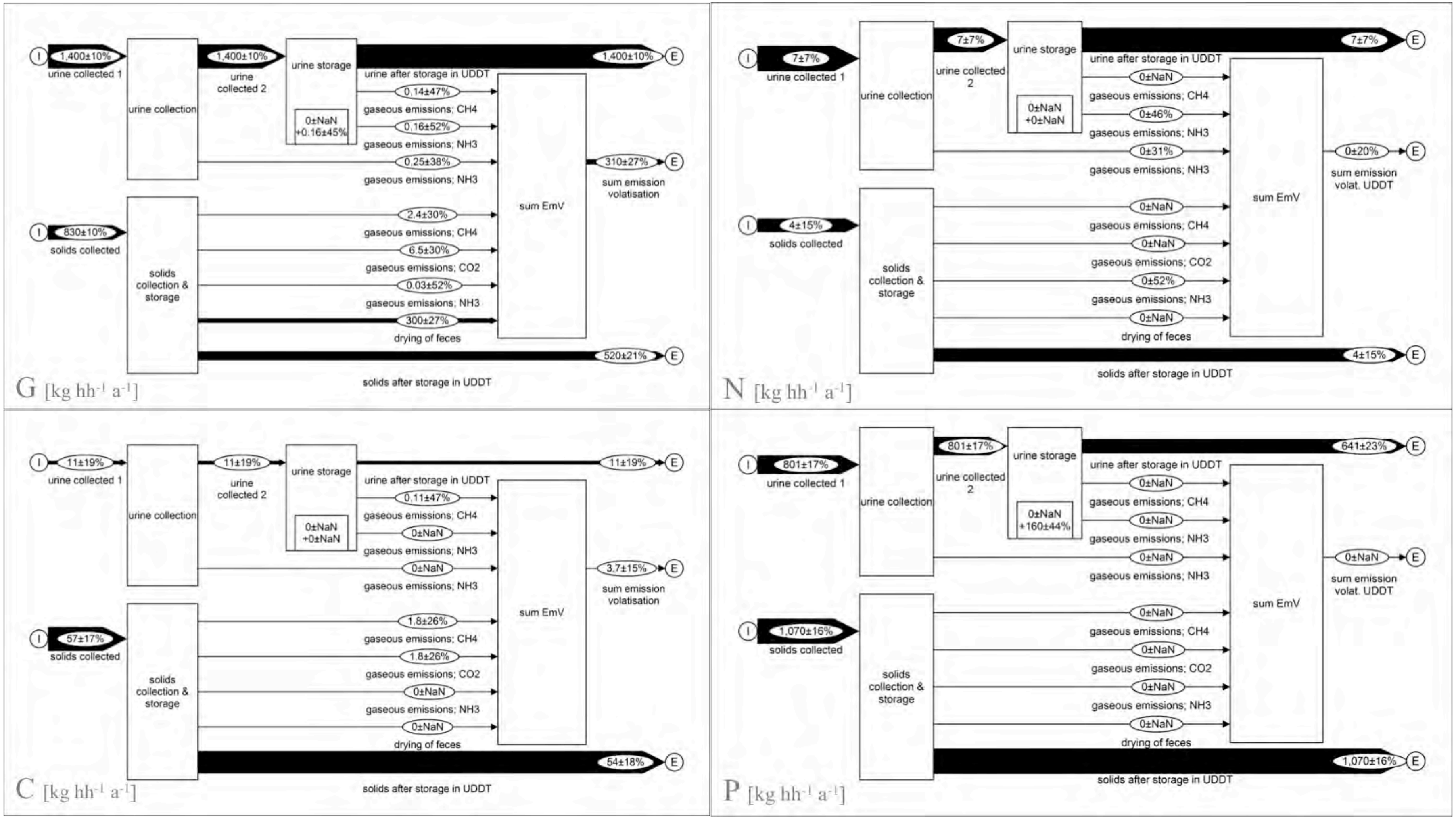


Fig. S.35: Flow diagrams of the sub-process 'toilet' analysed in the sub-process UDDT of the sanitation alternative S3, for the layer of goods (G) and indicator elements C, N, P in kg per household per year.

Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.



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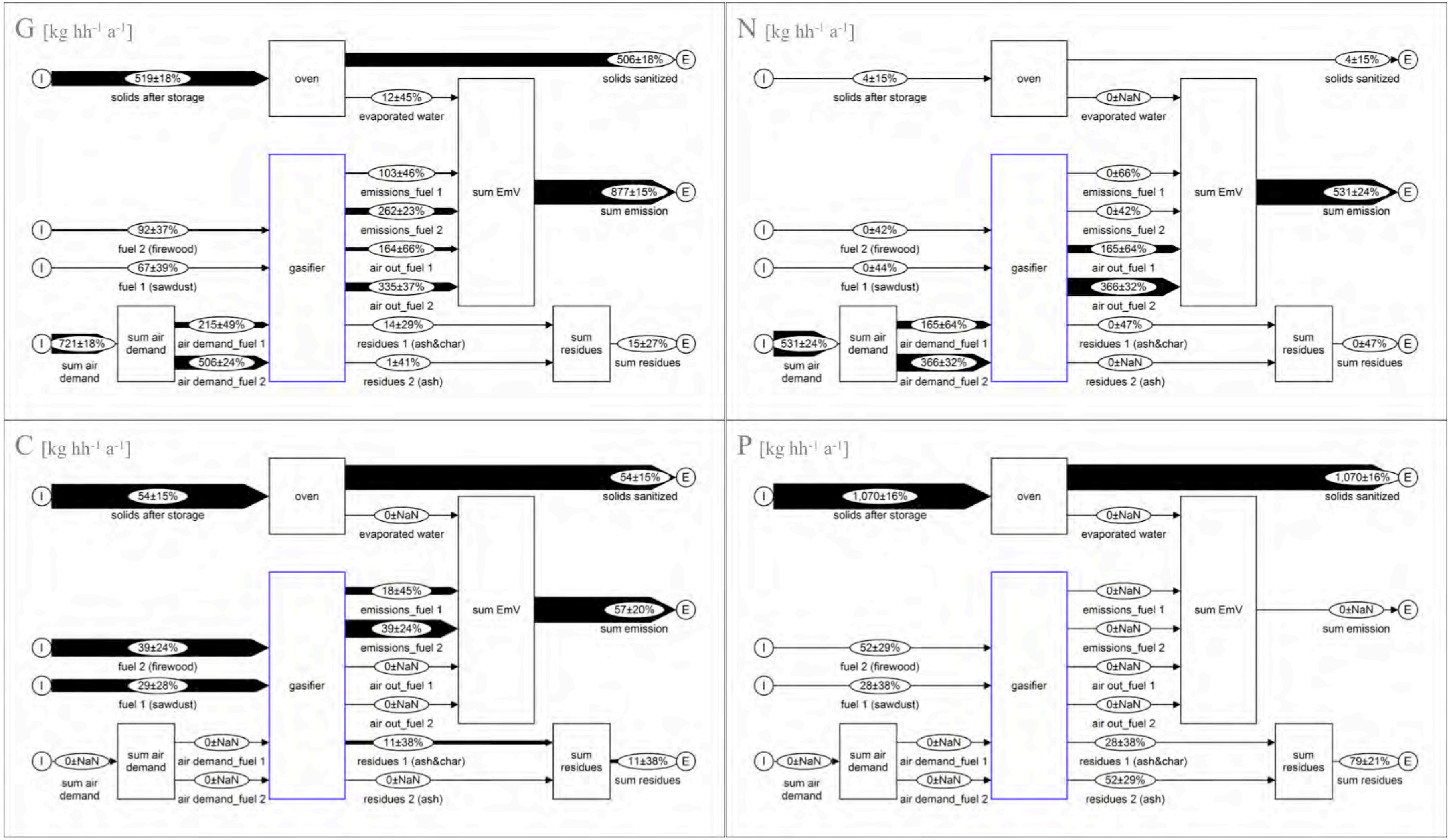
Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.



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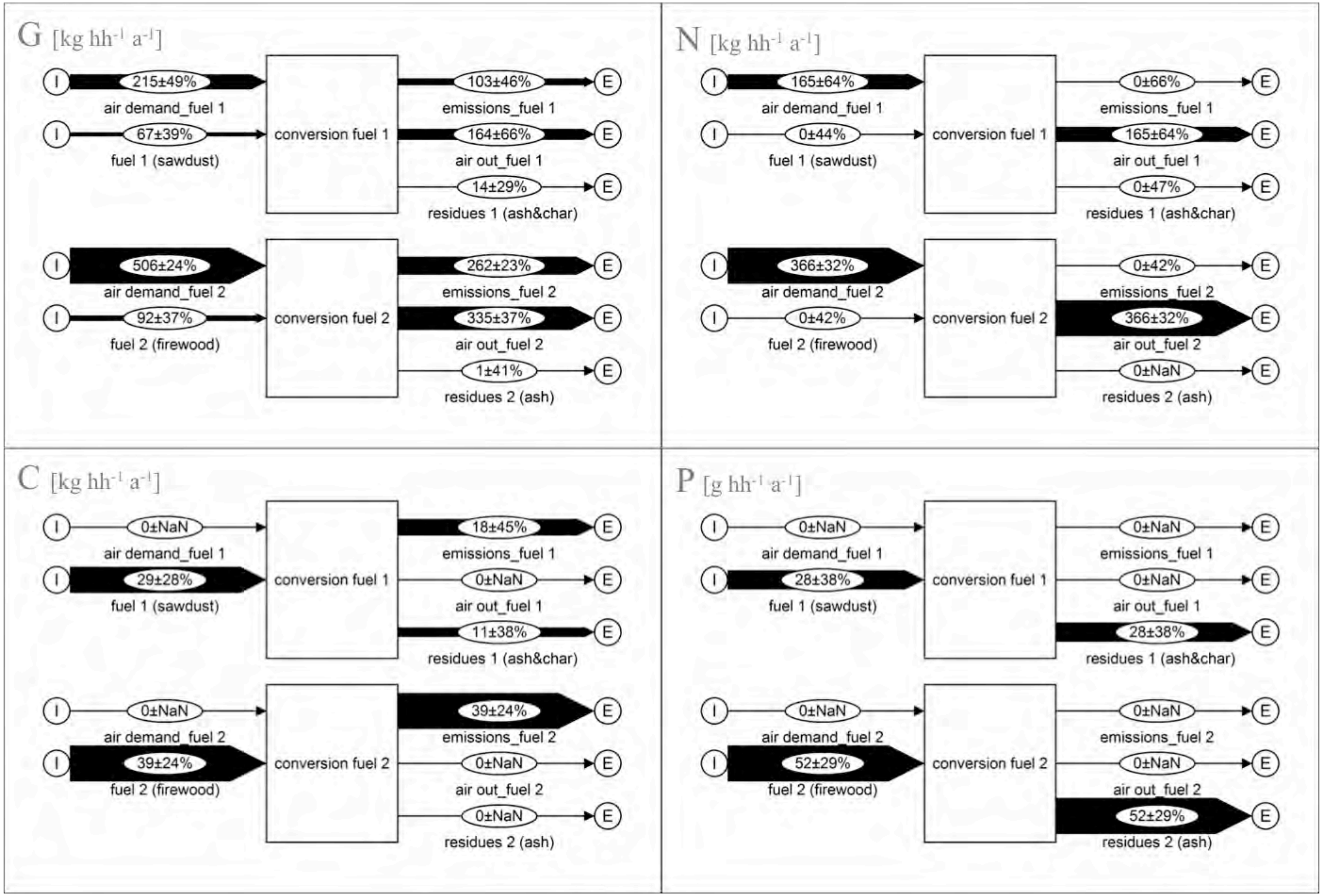

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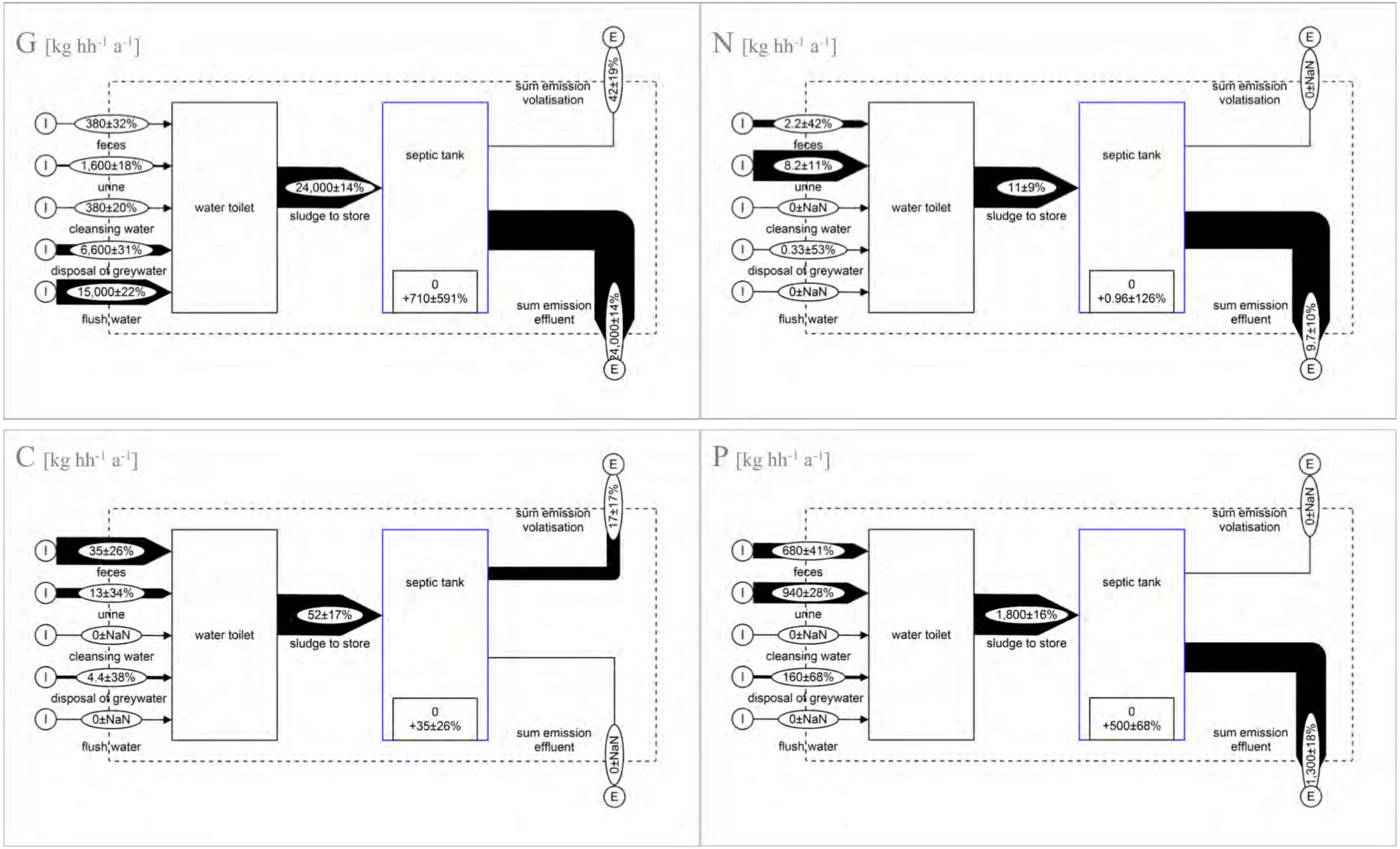
Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.



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Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

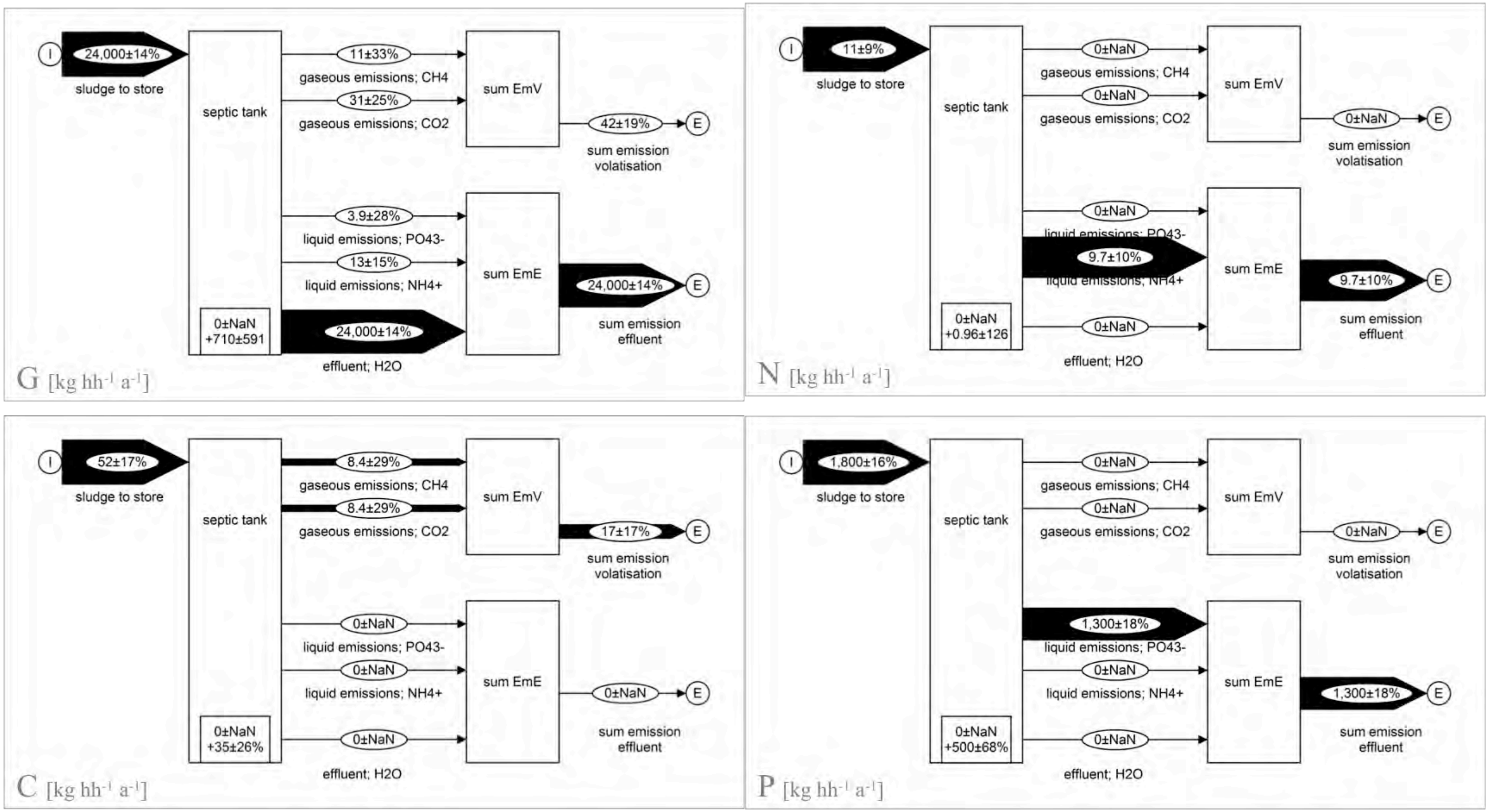

Fig. S.40: Flow diagrams of the sub-process 'septic tank' analysed in sanitation alternative S4, exemplarily shown for the variance S4_1 (see Table B.4) and for the layer of goods (G) and indicator elements C, N, P in kg per household per year.
Material flows are indicated with arrows including import flows (i) and export flows (E). Processes are indicated with boxes.

S3: Supplement of P4

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SUPPLEMENTARY MATERIAL OF

Recycling improves soil fertility management in smallholdings in Tanzania

A. Krause, V. S. Rotter
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

Table Content

FIGURES

Impressions of the main land-used types of cropping systems in Karagwe, TZ.

Fig. S.1: Example of a *shamba,* the agricultural land surrounding farming houses, also called ‘banana-based home garden’, used for inter-cropping of perennial crops like fruit, banana, and coffee trees and annual crops including beans, cassava, African egg-plant, etc. (Photo taken by A. Krause, 2010).

Fig. S.2: Example of a *msiri,* former grassland used for the cultivation of annual crops including maize, beans, millet, and vegetables like tomatoes, cabbage, onion, etc. (Photo taken by A. Krause, 2010).

Modelling approach of the system analysis applied to smallholder farming in Karagwe, TZ

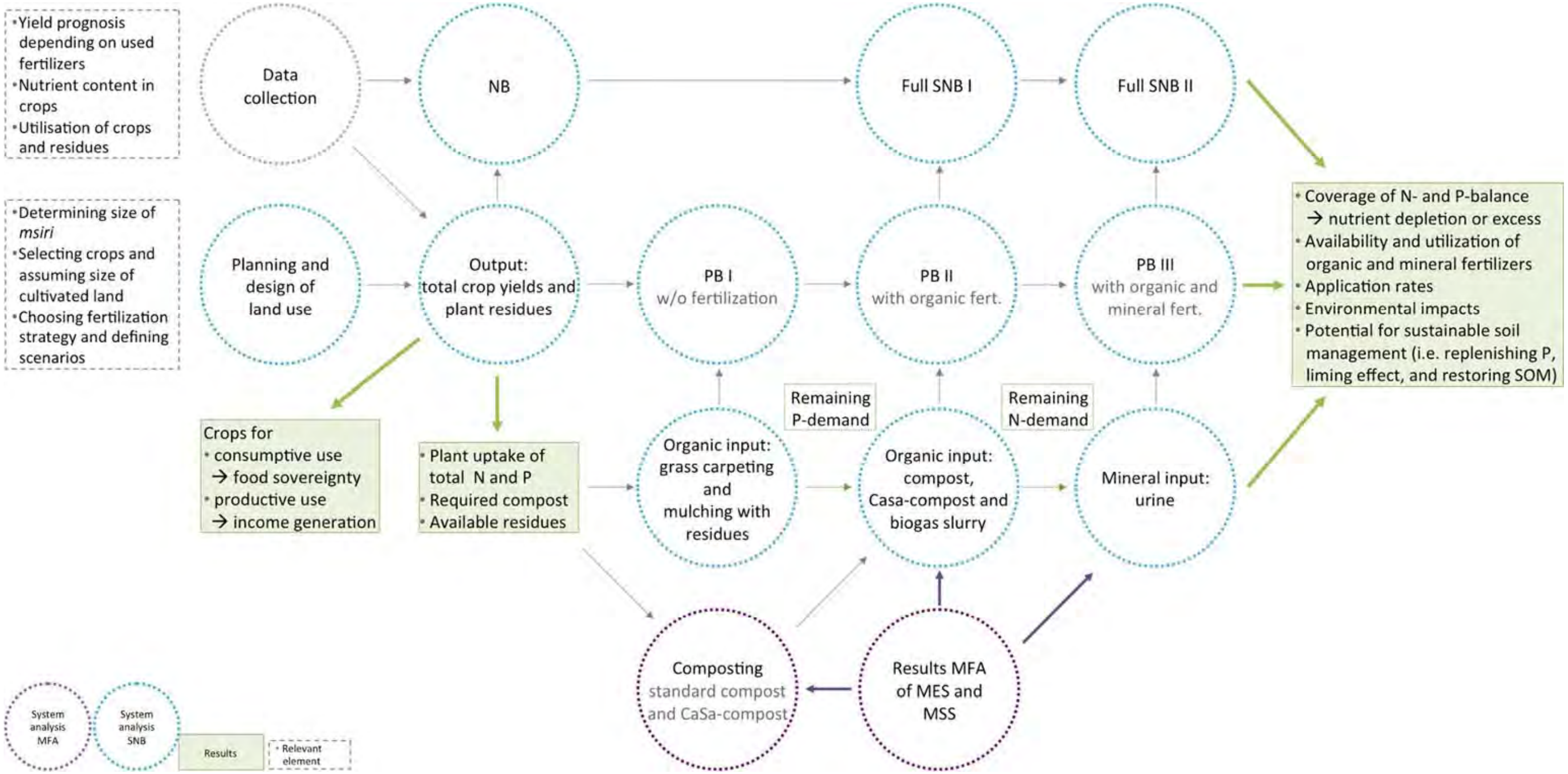
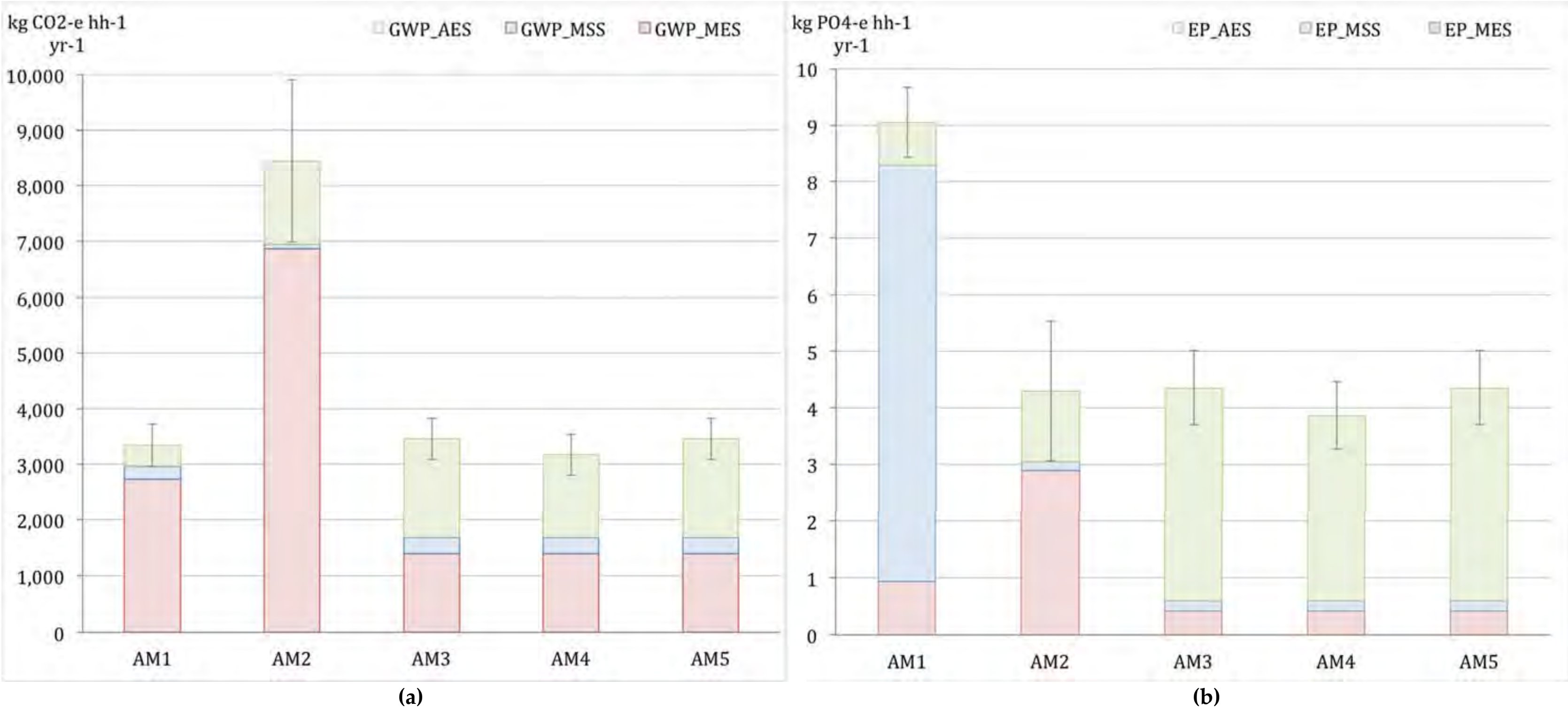


Fig. S.3: Proceeding of the applied system analysis combining the material flow analysis (MFA) with the soil nutrient balance (SNB) for an annual intercropping system in Karagwe, TZ



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Modelling the SNB: evaluation of data

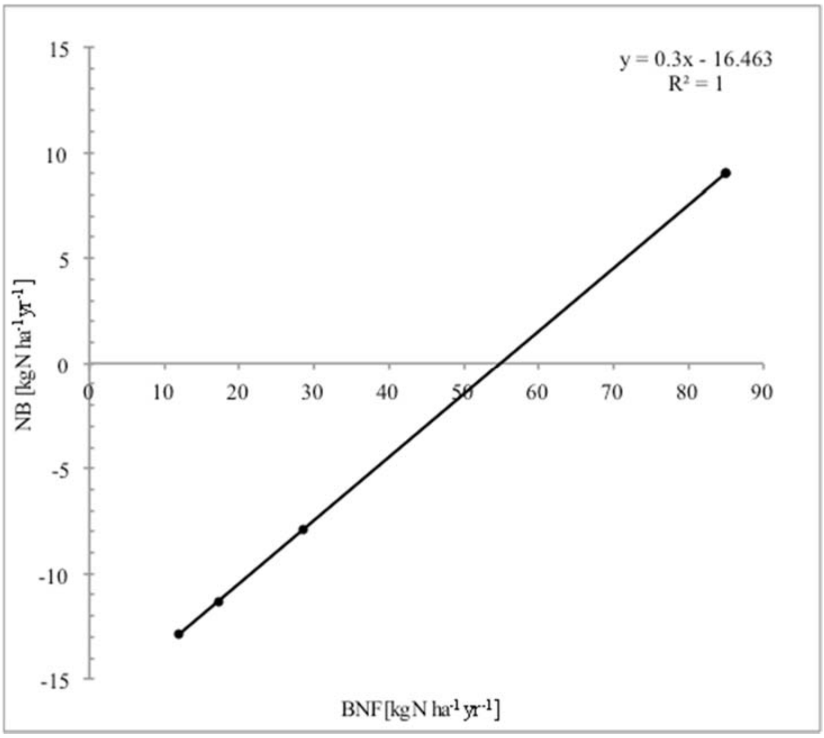

Fig. S.5: Regression analysis for estimating the relationships between the N-flows in the natural balance (NB) and the biological nitrogen fixation (BNF) for all of the five analysed scenarios; values are displayed in kg of N per hectare and year.
Plot data provided in Tables S.17

Summary of data describing the agroecosystem analysed

Table S.1: Production of main crops in Kagera region and Karagwe district based on the national sample census of agriculture 2007/2008 (Tanzania, 2012).

	Meaning of production in Kagera region	Meaning of production in Karagwe district	Total area planted in Karagwe [ha]	Number of household involved in crop production in Karagwe	Area planted per growing household in Karagwe [ha hh^{-1}]	Average yield (in FM) in Karagwe [t ha^{-1}]
Permanent crops:						
Banana	Main crop with about 50 % of the area used for permanent crops being cultivated with banana.	Largest area planted with banana within Kagera.	44,800	88,700	0.50	5.0
Coffee	Main cash crop.	Strongest coffee producing district in the region in terms of cultivated land and total harvest.	19,000	65,600	0.29	0.9
Annual crops – cereals and pulses/legumes:						
Beans	Dominant annual crop; production decreased by ~7.5 % compared to census 2003 (based on total area planted).	~37 % of the total area used for cultivation of annual crops and ~98 % of total production of pulses.	41,900	121,500	0.34	1.0
Maize	Second dominant annual crop; production of maize increased by ~20 % compared to census 2003 (based on the annual production).	~27 % of the total area used for cultivation of annual crops and ~77 % of the total land planted with cereal crops.	17,200	82,900	0.21	1.2
Annual crops – vegetables:						
Cabbage	Second important vegetable (after tomatoes).	Second largest production area in Kagera with ~20 % of land used for cabbage production in Kagera.	204	1,600	0.13	7.6
Onion	7th important vegetable.	Strongest producer in Kagera with nearly ~44 % of the land planted with onion in Kagera region.	75	700	0.11	2.8

Abbreviations: FM: fresh matter; hh: household.

Other important crops: permanent crops: mango, orange sugar cane; annual cereal crops: paddy (not in Karagwe), sorghum (especially in Karagwe), millet; annual root and tuber crops: cassava, sweet potatoes; annual oil seed crops: mainly groundnuts; minor soy beans and sunflower; annual vegetable crops: tomatoes, bitter aubergine, amaranth (spinach), chillies, pumpkins, okra, ginger; annual cash crops: tobacco and cotton are grown in Kagera, however not in Karagwe.

Summary of the technologies analysed

Table S.2: Pictures and short description of the analysed cooking alternatives that are locally available in Karagwe, TZ. Table adopted from Krause and Rotter, 2017; Table S26,Supplementary 1).

Three-stone-fire	Microgasifier stove		Biogas system	
	Sawdust gasifier	Top-Lit UpDraft	Biogas digester	Biogas burner
				
				 1-combuster, 2-pot stand
Easily prepared on-site. Continuous firing possible.	This advanced sawdust gasifier was developed in Karagwe by the local NGO CHEMA in cooperation with EWB. Production takes place at CHEMA local workshop. Distribution on local markets started 2017.	TLUD is an open source design. TLUD stoves are produced and distributed by a local NGO.	The BiogaST-digester was developed by the local NGO MAVNO in cooperation with EWB; the design follows the concept of a plug-flow digester.	CAMARTEC is Tanzanian producer and distributor of biogas burner of the design “Lotus 2”.
costs: *none*	31,000 TZS ≈12.50 € (selling price)	29,000 TZS ≈12 € (selling price)	≈ 3,000,000 TZS ≈1,200 € (material+labour costs)	60,000 TZS ≈24 € (selling price)
Residue: ash	biochar and ash		Biogas slurry	

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; NA: not analysed; TLUD: Top-Lit UpDraft˜

Sources of pictures: Three-stone fire: photo: http://www.lowtechmagazine.com/2014/06/thermal-efficiency-cooking-stoves.html; drawing: http://www.nzdl.org/gsdl/collect/envl/archives/HASH0165/064374a4.dir/p087a.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 S.3: Pictures and short description of the analysed sanitation alternatives that are locally available in Karagwe, TZ. Table adopted from Krause and Rotter, 2017).

Pit Latrine	EcoSan: UDDT only	CaSa: UDDT and sanitation oven
		
The substructure of the latrine toilet can be built from locally available material. Part of the grey water is disposed into the toilet, too. Often, ashes are added to the pit to avoid bad odours.	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 smelling. 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.	
The pit latrine is an accumulation system, i.e. material is constantly covered by new material. The pit is usually unlined so that the liquid phase soaks away and effluent infiltrates the surrounding soil. The solid phase remains in the pit and is slowly decomposed in predominantly anaerobic conditions.	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 rotation basis into a planting hole for a tree or cutting of a banana plant. This practice is locally called *omushote*.	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].
Made of mud/grasses, roofed with iron sheets: ≈ 250,000 TZS ≈ 100 € (labour costs). Made of bricks with roofing tiles: ≈ 900,000 TZS ≈ 360 € (material & labour costs)	≈ 450,000 TZS ≈ 180 € (material costs) ≈ 500,000 TZS ≈ 200 € (labour costs)	≈ 630,000 TZS ≈ 250 € (material costs) ≈ 500,000 TZS ≈ 200 € (labour costs)

Non-common abbreviations: CaSa-project “Carbonization and Sanitation”; EcoSan: ecological sanitation; UDDT: urine-diverting dry toilet; TZS: Tanzanian shilling.
Notes: Costs were transferred from TZS to € by applying an exchange rate of 1,000 TZS = ≈0.40 €. // Sources for the costs: Expert judgement (Mavuno, 2015) for S1 and S4; CaSa project-accounting, pilot phase 2012 for S2 and S3.
Sources: Pit latrine: photo: A. Krause; drawing: Brikké and Bredero, 2003;
UDDT: photo: A. Krause; drawing: http://www.ingenieure-ohne-grenzen.org/de/content/download/23394/134705/file/How%20to%20build%20a%20UDDT%20–%20Construction%20Manual%20–%20English.pdf;
CaSa: photo: A. Krause; drawing: http://www.ingenieure-ohne-grenzen.org/de/content/download/23393/134699/file/How%20to%20build%20an%20oven%20–%20Construction%20Manual%20–%20english.pdf

[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.

Modelling the SNB: system definition

Table S.4: Definition of the system analysed

Defining element	Description of the farming system
Problem description	Continuously declining soil fertility due to the lack of available organic fertilizers. Locally available residues from cooking and sanitation are not yet integrated in the soil fertility management.
Developed countermeasures	Local initiatives recently started testing IPNM-strategies including the use of (i) biogas slurry as organo-mineral fertilizer; (ii) stored urine as mineral fertilizer; (iii) 'CaSa-compost' containing sanitized human excreta mixed with biochar and other domestic residues, prepared according to the principles of Terra Preta; (iv) standard compost containing ashes, harvest residues, and kitchen residues.
Specific objective	Comparison of the soil management in Karagwe at the current state with specific IPNM-strategies regarding effects on (i) soil nutrient balances, (ii) subsistence production of compost, and (iii) environmental emissions.
Activities	To subsist, which for the AES specifically comprises (i) to make compost and (ii) to grow locally relevant food crops, which includes cultivating staple crops, legumes, and vegetables.
Spatial system boundary	One smallholder farm in Karagwe including the land used for the intercropping of annual crops (land called msiri) at 0.125 ha. The msiri was used for growing maize, beans, onion, and cabbage on 80 %, 15 %, 2.5 %, and 2.5 % of the land, respectively.
Temporal boundary	One year with two seasons, or two cultivation periods.
Indicator substances	C as structural element of SOM; N and P as essential plant nutrients in farming.

Abbreviations: IPNM: integrated plant nutrient management; SOM: soil organic matter

Modelling the SNB: results used in discussion

Table S.5: Estimated application rates of the organic and mineral inputs studied in scenarios AM1-AM5 in kg of FM per household and year

	Application rate				
	Standard compost	CaSa-compost	Biogas slurry	Urine: maize	Urine: vegetables
Alternative	kg m^{-2} yr^{-1}	kg m^{-2} yr^{-1}	dm^3 m^{-2} $season^{-1}$	dm^3 m^{-2} $season^{-1}$	dm^3 m^{-2} $season^{-1}$
AM1	4.4 ±1.4	NA	NA	NA	3.6 ±1.8
AM2	2.8 ±1.0	NA	3.2 ±1.0	0.3 ±0.3	1.7 ±1.0
AM3	2.6 ±0.5	1.8 ±0.2	NA	0.2 ±0.03	1.6 ±0.7
AM4	2.0 ±0.5	1.7 ±0.1	NA	0.1 ±0.04	2.0 ±0.7
AM5	11.3 ±1.8	5.5 ±0.5	NA	0.5 ±0.3	0.5 ±0.1

Abbreviations: CaSa-compost: compost produced in project 'Carbonizations and sanitation'; FM: fresh matter; NA: not analysed (i.e. not considered in scenario)

Table S.6: Estimated P-inputs with organic and mineral inputs studied in scenarios AM1-AM5 in kg of P per hectare and year

	P-inputs		
	Standard compost	CaSa-compost	Biogas slurry
Alternative	kg P ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}	kg P ha^{-1} yr^{-1}
AM1	62 ±21	NA	NA
AM2	32 ±12	NA	21 ±9
AM3	29 ±10	38 ±6	NA
AM4	25 ±11	35 ±6	NA
AM5	154 ±51	113 ±17	NA

Abbreviations: CaSa-compost: compost produced in project 'Carbonizations and sanitation'; NA: not analysed (i.e. not considered in scenario); P: Phosphorus

Table S.7: Estimated liming effects of the organic material expressed in equivalent application in kg of CaO per hectare and year calculated with liming potentials presented in Krause et al. (2015)

	Liming effect		
	Standard compost	CaSa-compost	Biogas slurry
Alternative	kg CaO ha^{-1} yr^{-1}	kg CaO ha^{-1} yr^{-1}	kg CaO ha^{-1} yr^{-1}
AM1	428 ±146	NA	NA
AM2	299 ±100	NA	229 ±115
AM3	276 ±78	652 ±109	NA
AM4	225 ±76	637 ±126	NA
AM5	1,362 ±303	1,957 ±333	NA

Abbreviations: CaO: lime; CaSa-compost: compost produced in project 'Carbonizations and sanitation'; NA: not analysed (i.e. not considered in scenario)

Table S.8: Estimated C-inputs with organic and mineral inputs studied in scenarios AM1-AM5 in kg of C per hectare and year

	C-inputs					
	Standard compost		CaSa-compost		Biogas slurry	
Alternative	kg C ha^{-1} yr^{-1}		kg C ha^{-1} yr^{-1}		kg C ha^{-1} yr^{-1}	
AM1	3,897	±1,316	NA		NA	
AM2	3,412	±1,426	NA		1,025	±438
AM3	2,960	±1,276	2,607	±617	NA	
AM4	2,835	±1,362	2,374	±634	NA	
AM5	18,076	±5,414	7,822	±1,851	NA	

Abbreviations: C: Carbon; CaSa-compost: compost produced in project 'Carbonizations and sanitation'; NA: not analysed (i.e. not considered in scenario)

Table S.9: Estimated SOM reproduction potentials with organic and mineral inputs studied in scenarios AM1-AM5 in kg of C in SOM per hectare and year

	SOM-C-inputs					
	Standard compost		CaSa-compost		Biogas slurry	
Alternative	kg SOM-C ha^{-1} yr^{-1}		kg SOM-C ha^{-1} yr^{-1}		kg SOM-C ha^{-1} yr^{-1}	
AM1	1949	±658	NA		NA	
AM2	1706	±713	NA		256	±110
AM3	1480	±638	1304	±308	NA	
AM4	1417	±681	1187	±317	NA	
AM5	9038	±2707	3911	±925	NA	

Abbreviations: C: Carbon; CaSa-compost: compost produced in project 'Carbonizations and sanitation'; NA: not analysed (i.e. not considered in scenario; SOM: soil organic matter

Table S.10: Available materials for organic and mineral fertilization in kg yr^{-1} of FM

	Available organic and mineral input materials											
	Total residues		Residues used for mulching		Standard compost		CaSa-compost		Biogas slurry		Urine	
Alternative	kg yr-1											
AM1	993	±118	468	±60	346	±48	NA		NA		NA	
AM2	1567	±188	740	±96	476	±69	NA		14955	±3118	1364	±184
AM3	2793	±273	1318	±158	235	±37	2183	±210	NA		583	±193
AM4	1898	±214	896	±113	168	±26	2026	±194	NA		583	±193
AM5	2793	±273	1318	±158	235	±37	2183	±210	NA		583	±193

Abbreviations: FM: fresh matter; NA: not analysed, i.e. the respective matter was not considered in this scenario. Scenarios are defined in Table 3. Mulching material was 47 ± 6.5 % of total agricultural residues and completely utilized.

Table S.11: Utilization of the matter as input material in % of available FM.

	Utilization							
	Standard compost		CaSa-compost		Biogas slurry		Urine	
Alternative	%							
AM1	40	±14	NA		NA		NA	
AM2	37	±26	NA		51	±19	65	±58
AM3	69	±17	100	±0	NA		100	±35
AM4	75	±21	100	±8	NA		99	±18
AM5	100	±0	100	±0	NA		100	±6

Abbreviations: FM: fresh matter; NA: not analysed, i.e. the respective matter was not considered in this scenario. Scenarios are defined in Table 3. Mulching material was 47 ± 6.5 % of total agricultural residues and completely utilized.

Modelling the SNB: plot data to results presented in figures

Table S.12: Estimated SNB for N and P comprising natural input (IN3a, 4a, 4b) and natural output (OUT3, 4a) flows; organic (IN2a-2e) and mineral (IN1c) input flows; and output flows (Out1a, 1b, 2) with agricultural products; in kg of N and P per household and year; plot data for Fig. 3.

Flow Name	Abbrev.	AM1	AM2	AM3	AM4	AM5	AM1	AM2	AM3	AM4	AM5
		kg N ha^{-1} yr^{-1}					kg P ha^{-1} yr^{-1}				
Own consumption	OUT1a	-23.8	-44.0	-67.0	-51.2	-67.0	-4.8	-9.2	-15.6	-11.0	-15.6
Sold to market	OUT1b	-8.4	-18.1	-30.3	-21.9	-30.3	-2.2	-4.5	-9.4	-5.7	-9.4
Harvest residues total	OUT2	-34.3	-55.4	-94.7	-66.7	-94.7	-8.9	-14.8	-26.7	-18.1	-26.7
Grass carpet	IN2a	5.3	5.3	5.3	5.3	5.3	0.9	0.9	0.9	0.9	0.9
Mulching with crop residues	IN2b	15.4	24.6	47.4	30.4	47.4	4.2	7.0	12.6	8.5	12.6
Compost (for cabbage)	IN2c	4.1	5.8	5.3	4.4	8.8	1.5	1.6	1.4	1.3	2.6
CaSa-compost	IN2d	NA	NA	79.7	72.9	79.7	NA	NA	35.8	33.2	35.8
Biogas slurry	IN2e	NA	51.8	NA	NA	NA	NA	20.1	NA	NA	NA
Urine	IN1c	NA	30.1	19.8	19.6	19.8	NA	3.3	2.2	2.2	2.2
Leaching	OUT3	-12.3	-12.3	-12.3	-12.3	-12.3	NA	NA	NA	NA	NA
Gaseous losses, denitrification	OUT4a	-13.8	-13.8	-13.8	-13.8	-13.8	NA	NA	NA	NA	NA
Atmospheric deposition - wet	IN3a	6.4	6.4	6.4	6.4	6.4	0.9	0.9	0.9	0.9	0.9
BNF_symbiotic	IN4a	3.6	5.2	25.5	8.6	25.5	NA	NA	NA	NA	NA
BNF_asymbiotic	IN4b	3.3	3.3	3.3	3.3	3.3	NA	NA	NA	NA	NA
Full SNB	SNB	-54	-11	-25	-15	-22	-8	6	2	12	3
NB	NB	-13	-11	9	-8	9	0.9	0.9	0.9	0.9	0.9

Abbreviations: BNF: symbiotic biological nitrogen fixation; CaSa-compost: compost produced in project 'Carbonizations and sanitation'; NA: not analysed (i.e. not considered in scenario); NB: natural balance; SNB: soil nutrient balance. Alternatives AM1-AM5 are defined in Table 3.

Table S.13: Estimated environmental impacts of the analysed IPNM-strategies: the global warming potential in kg of CO_2 equivalents per household and year; plot data for Fig. 5a

Flow Name	Abbrev.	AM1	AM2	AM3	AM4	AM5
		kg CO_2-e hh^{-1} yr^{-1}				
Carpeting and mulching	N_2O	40.4	58.5	103.0	69.8	103.0
Burning residues	CO_2	19.2	30.4	54.1	36.8	54.1
Burning residues	CO	2.3	3.7	6.6	4.5	6.6
Burning residues	CH_4	1.0	1.5	2.7	1.8	2.7
Burning residues	N_2O	0.2	0.4	0.7	0.5	0.7
Burning residues	Nox	-0.3	-0.6	-1.0	-0.7	-1.0
Composting	CO_2	281	409	205	145	205
Composting	N_2O	36.4	49.0	28.1	19.0	28.1
CaSa-composting	CO_2	NA	NA	1127.4	987.4	1127.4
CaSa-composting	N_2O	NA	NA	227.1	205.9	227.1
Biogas slurry	N_2O	NA	921.15	NA	NA	NA
Urine	N_2O	NA	32.5	21.4	21.2	21.9
Total	Sum	380	1506	1775	1491	1776

Abbreviations: hh: household; IPNM: integrated plant nutrient management; NA: not analysed (i.e. not considered in scenario)

Table S.14: Estimated environmental impacts of the analysed IPNM-strategies: the eutrophication potential in kg of PO_4 equivalents per household and year; plot data for Fig. 5b

Flow Name	Abbrev.	AM1	AM2	AM3	AM4	AM5
		kg PO_4-e hh^{-1} yr^{-1}				
Carpeting and mulching	NH_3	0.15	0.21	0.37	0.25	0.37
Burning residues	NO_x	0.00	0.01	0.01	0.01	0.01
Composting	NH_3	0.35	0.51	0.27	0.18	0.27
Composting	P-leaching	0.25	0.14	0.07	0.05	0.07
CaSa-composting	NH_3	0.00	0.00	2.21	2.00	2.21
CaSa-composting	P-leaching	0.00	0.00	0.69	0.64	0.69
Biogas slurry	NH_3	0.00	0.03	0.00	0.00	0.00
Biogas slurry	N-leaching	0.00	0.14	0.00	0.00	0.00
Urine	NH_3	0.00	0.13	0.09	0.09	0.09
Urine	N-leaching	0.00	0.07	0.05	0.05	0.05
Total	Sum	0.75	1.25	3.76	3.27	3.76
Total (without P-leaching)	Sum	0.50	1.11	3.00	2.58	3.00

Abbreviations: hh: household; IPNM: integrated plant nutrient management; NA: not analysed (i.e. not considered in scenario)

Table S.15 Integrated environmental impacts with GWP of the MES, the MSS, and the AES in kg of CO_2 equivalents per household and year; plot data for Fig. S.4a

	AM1	AM2	AM3	AM4	AM5
	kg CO_2-e hh^{-1} yr^{-1}				
GWP_MES	2742	6870	1401	1401	1401
GWP_MSS	218	77	282	282	282
GWP_AES	380	1506	1775	1491	1776
Sum	3340	8452	3459	3175	3459

Abbreviations: AES: agroecosystem; GWP: global warming potential; hh: household; MES: micro energy systems; MSS: micro sanitation system

Table S.16 Integrated environmental impacts with EP of the MES, the MSS, and the AES in kg of PO_4 equivalents per household and year; plot data for Fig. S.4b

	AM1	AM2	AM3	AM4	AM5
	kg PO_4-e hh^{-1} yr^{-1}				
EP_MES	0.9	2.9	0.4	0.4	0.4
EP_MSS	7.4	0.2	0.2	0.2	0.2
EP_AES	0.8	1.2	3.8	3.3	3.8
Sum	9.0	4.3	4.4	3.9	4.4

Abbreviations: AES: agroecosystem; EP: eutrophication potential; hh: household; MES: micro energy systems; MSS: micro sanitation system

Table S.17: Evaluation SNB – regression analysis: estimated biological N fixation and estimated natural balance in kg of N per household and year; plot data for Fig. S.3

	BNF		NB	
Scenario	kg N hh^{-1} yr^{-1}		kg N hh^{-1} yr^{-1}	
AM1	12	±3	-13	±5
AM2	17	±4	-11	±5
AM3/5	85	±17	9	±6
AM4	29	±7	-8	±5

Abbreviations: BNF: symbiotic biological nitrogen fixation; hh: household; NB: natural balance; SNB: soil nutrient balance

Modelling composting processes: plot data to results presented in figures

Table S.18: Relative contribution of the different resources used for standard composting and for CaSa-composting to the total input flow in terms of volume and content of C, N, and P prior to the composting process in %; plot data for Fig. 4a

Alternative	AM1	AM2-5 (average)			AM1	AM2-5 (average)		
	Vol.	C	N	P	Vol.	C	N	P
Input flow	vol-%		wt-%		vol-%		wt-%	
Harvest residues	0.85	0.79	0.75	0.28	0.93	0.88	0.86	0.84
Kitchen waste	0.12	0.21	0.25	0.09	0.06	0.12	0.14	0.12
Ashes (from agriculture)	0.00	NA	NA	0.01	0.00	NA	NA	0.04
Ashes (from cooking)	0.03	NA	NA	0.62	NA	NA	NA	NA

Abbreviations: C: carbon; N: nitrogen; NA: not analysed (i.e. not considered in scenario); P: phosphorus; Vol: volume; wt: weight

Table S.19: Relative contribution of the different resources used for standard composting and for CaSa-composting to the total input flow in terms of volume and content of C, N, and P prior to the composting process in %; plot data for Fig. 4b

Alternative	AM3-5 (average)			
	Vol.	C	N	P
Input flow	vol-%		wt-%	
Sanitized solids (from UDDT)	0.15	0.09	0.25	0.25
Biochar (from sanitation)	0.01	0.02	0.00	0.02
Biochar (from cooking)	0.17	0.38	0.06	0.14
Harvest residues	0.40	0.34	0.22	0.18
Kitchen waste	0.02	0.04	0.03	0.02
Ashes (from agriculture)	0.06	0.0	0.0	0.01
Sawdust	0.01	0.07	0.02	0.01
Soil	0.19	0.05	0.15	0.26

Abbreviations: C: carbon; N: nitrogen; P: phosphorus; UDDT: urine diverting dry toilet; Vol: volume; wt: weight

Modelling the SNB: additional results of food production

Table S.20: Material output flows of *food products* (i.e. maize and beans grains, cabbage heads, and onion bulbs) in kg of FM (after air-drying for maize, beans, and onion) per household and year

	Maize		Beans		Cabbage		Onion	
Alternative	kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}	
AM1	243	±6	25	±4	258	±58	24	±6
AM2	525	±66	35	±11	258	±58	88	±10
AM3/5	877	±103	184	±21	258	±58	88	±10
AM4	636	±75	60	±15	258	±58	88	±10

Abbreviations: hh: household; FM: fresh matter

Table S.21: Material output flows of *food products for self-consumption* in kg of FM (after air-drying for maize, beans, and onion) per household and year

	Maize		Beans		Cabbage		Onion	
Alternative	kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}	
AM1	159	±32	9	±2	258	±77	24	±8
AM2	344	±81	13	±5	258	±77	88	±20
AM3/5	574	±133	70	±16	258	±77	88	±20
AM4	417	±97	23	±7	258	±77	88	±20

Abbreviations: hh: household; FM: fresh matter

Table S.22: Material output flows of *food products sold to market* in kg of FM (after air-drying for maize, beans, and onion) per household and year

	Maize		Beans		Cabbage		Onion	
Alternative	kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}	
AM1	84	±17	15	±4	0	±0	0	±0
AM2	181	±43	22	±8	0	±0	0	±0
AM3/5	303	±70	114	±26	0	±0	0	±0
AM4	219	±51	37	±12	0	±0	0	±0

Abbreviations: hh: household; FM: fresh matter

Table S.23 Material output flows of *harvest residues* in kg of FM (at time of harvesting) per household and year

	From maize		From beans		From cabbage		From onion		Total	
Alternative	kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}		kg hh^{-1} yr^{-1}	
AM1	763	±82	37	±8	189	±84	4	±1	993	±118
AM2	1,318	±167	53	±8	189	±84	7	±2	1,567	±188
AM3/5	2,353	±259	245	±18	189	±84	7	±2	2,793	±273
AM4	1,616	±196	87	±13	189	±84	7	±2	1,898	±214

Abbreviations: hh: household; FM: fresh matter

Table S.24: Relative uncertainties (RU) of results calculated defined as the standard error in % of the arithmetic mean value

	Nutrient requirement of crops		Nutrient supply with organic and mineral fertilization		Natural balance		Full SNB with organic and mineral fertilization	
Alternative	N	P	N	P	N	P	N	P
AM1	4%	9%	2%	1%	15%	35%	5%	12%
AM2	4%	8%	16%	15%	17%	35%	125%	63%
AM3	4%	8%	8%	12%	25%	35%	38%	224%
AM4	8%	17%	18%	18%	69%	35%	112%	43%
AM5	4%	8%	11%	16%	25%	35%	50%	163%

Abbreviations: N: nitrogen; P: phosphorus; RU: relative uncertainty
According to Laner et al. (2013), RU-values of < 30 %, ± 50 %, or > 90 % indicate low, average, or high uncertainty, respectively.

Preliminary remark to the appendix for the modelling approach

Supplementary 1 first briefly introduces basic definitions of the agroecosystem (AES). We outline the farming system analysed for the case of smallholder farming in Karagwe, in Northwest Tanzania (TZ) (S1.1), describe the scenarios studied including farming practices considered (S1.2), explain the method applied for modelling as well as the general structure of the model (S1.3). We also disclose the basic assumptions that we took, including those for simplifying the model to make it applicable in the present context (S1.4). The first chapter ends with an annotated list of selected flows of the model presented in Table S27. In Chapter S2, we explain the sets of equations used to systematically quantify relevant material flows while modelling the AES (S2) including composting processes (S2.6). In S3, we briefly explain how we assessed the environmental emissions. In S4 we shortly discuss selected assumptions and simplification in addition to the major discussion as part of the main article. In S5, we provide information about our data collection and a list of all parameter values used (Table S32). In S6, we list specific words which we use in this document.

Supplementary 1.

1.1. Basic description of the agroecosystem analysed.

The basic definition of the AES-model includes (i) the 'housing system', representing the farming household, (ii) the 'farming system', describing the size of planted farmland, and (iii) the 'land use' (LU), describing the distribution of land for selected crops (Table S25). The farming household further comprises the micro energy system (MES) and the micro sanitation system (MSS), and has been systematically analysed in Krause and Rotter (2017). The total planted farmland consists of fields called *msiri*, used for growing annual crops, and fields called *shamba,* used for growing perennial crops. Only the *msiri* are included in the present analysis. The housing system and farming system are connected through a composting process, which is assigned to the farming system. *Locally available materials* for composting and fertilization include resources recovered from cooking in the MES and sanitation, i.e. from the MSS (*ibid*.).

Table S25: Basic description of the AES.

Housing system		Farming system		Land use of the *msiri*	
Number of people per family:	6	Total size of planted farmland:	0.625 ha	Maize	80%
Number of families:	1	Size of planted farmland used as *shamba.*	0.5 ha	Beans	15%
Years of modelling:	1	Size of planted farmland used as *msiri:*	0.125 ha	Onion	2.5%
Cultivation periods per year:	2			Cabbage	2.5%

The **temporary system boundary** of the model is one year. The **spatial system boundary** includes the *msiri* and refers to a typical smallholder farm in Karagwe (cf. Table 1 in main article). The modelling is done in the layers of goods (G), and indicator substances include carbon (C), nitrogen (N), and phosphorus (P). One farming year includes two cropping seasons. The model factor (MF; in ha yr^{-1}) reflects the total cultivation area per year (Eq.S1) and is the product of the two cultivation periods per year ($periods_{\,cult.}$) and the size of the planted farmland used as *msiri* ($area_{msiri}$). The MF is used in most equations, in combination with the LU, to estimate crop specific **annual material flows ($\dot{m}$** in kg yr^{-1}), such as in- and output flows of nutrients to and from the farmland, respectively (see Supplementary S2).

$$MF = periods_{\,cult.} \cdot area_{msiri} = 2 \cdot 0.125 \qquad \text{Eq. (S1)}$$

In sum, **five scenarios** are compared for the agricultural system *msiri* (AM1-5). Each scenario represents a strategy of *integrated plant nutrient management* (IPNM). Hence, scenarios are principally defined by the fertilization strategy applied specifying different fertilizer inputs used, including residues recovered from the farming household. Overall, the current state farming practices (AM1), where mineral and organic material inputs ($\dot{m}_{input}$) are exclusively used for cultivating cabbage, are compared to the use of biogas slurry as an organic $\dot{m}_{input}$ in combination with urine as a mineral $\dot{m}_{input}$ (AM2), and to the use of CaSa-compost as an organic $\dot{m}_{input}$ in combination with urine as a mineral $\dot{m}_{input}$ (AM3-5) (cf. Supplementary 1.3).

Before going more into detail about the scenarios analysed, we briefly elaborate system definition, which we based on local conditions. To describe agricultural activities as common in the region, we refer to the **national census** of agriculture in the Kagera region (Tanzania, 2012) and available monitoring data of the partner organisation MAVUNO Project (Mavuno, 2015):

- On average, the total area available to one smallholder farm in Karagwe is approx. 0.75 ha **usable land** (equivalent to approx. 2 acres).
- Approximately 83 % of this land is used for agriculture, which results in approx. 0.625 ha of **planted land** per household.
- From the total planted land, 0.5 ha are allocated to *shamba* and **0.125 ha to *msiri***.
- We only consider **locally available residues as organic inputs** to farmland, such as biogas slurry, compost, and CaSa-compost as well as urine as a **mineral input**.
- Use of **animal manure is not considered** because the present analysis focussed on (i) structurally poor households that generally do not possess animals and (ii) vegan organic farming.
- **Synthetic fertiliser are not used** because (i) most smallholders practice organic agriculture and (ii) there is a general lack of financial or logistical access to commercial fertilizers. According to national statistics, commercial synthetic fertilizers are used on less than 1 % of the planted land in Karagwe whilst about 78 % of the farmers who apply fertilizers use organic fertilizer.
- For the cultivation of food crops we focus on locally cultivated and nutrition-relevant food crops and selected **maize** as a staple food, **beans** as a legume food, and **cabbage** and **onion** as vegetables.
- We assumed that maize, beans, and vegetables are cultivated on, respectively, 1,000, 187.5, 62.5 m^2 of *msiri* farmland. The area for vegetables is further distributed to onion and cabbage by 50 % each.
- Beans are important in the local AES by contributing to the input of N through symbiotic **biological nitrogen fixation** (BNF).
- **Plant growth** is assumed based on the field experiment, which we conducted in Karagwe in 2014 (Krause et al., 2016). From this experiment, we have specific results for total biomass production and crop yields available for each of the four crops corresponding to the use of biogas slurry, standard compost, CaSa-compost, or no fertilizing input (i.e. 'current state').
- In order to reduce the evapotranspiration of soil, water, and wind-erosion during dry seasons, the ground is commonly covered with grass cuttings (**'grass carpeting'**) and a certain share of agricultural residues for **'mulching'**, respectively.

1.2. Definition of scenarios defined.

The following paragraph presents the IPNM-strategies analysed, respectively scenarios AM1-AM5, in more detail.

In the scenario reflecting the **current state** of soil fertility management **(AM1),** only standard compost is used as an organic input, and *only* for cabbage due to the following reasons: (I) In general, most farmers in Karagwe and Kagera do not use fertilizers (see above). (II) It is barely possible to cultivate cabbage in the region without the addition of fertilizer (Krause et al., 2016; Mavuno, 2015). Therefore, applying compost to the area planted with cabbage is defined as a 'minimum requirement' in current cultivation practices.

The **Karagwe standard compost** (Fig. 1) is prepared from locally available residues including grasses, harvest residues, and ashes which are residues from cooking with a three-stone fire (Krause et al., 2015). The composting process is modelled as part of the present AES-model (Supplementary 2.6.I). The amount of ashes available from cooking that can be used for composting is quantified in Krause and Rotter (2017) in alternative E1 in the MES-model. The assumed biomass growth and crop yields used for modelling AM1 are based on a mean value for unamended soils in Krause et al. (2016) combined with literature values, specific to the region.

Figure S6: Locally produced Karagwe standard compost (own picture, March 2014).

In **scenario AM2**, biogas slurry is used as an organic fertilizer, which is available as residue from using small-scale biogas digesters. The slurry is used for fertilizing only the area cultivated with maize and beans. The area cultivated with vegetables, both cabbage and onion, is amended with standard compost. In addition, urine is used as mineral fertilizer for all crops. The available amount of biogas slurry from cooking that can be used for fertilization is quantified in Krause and Rotter (2017) in alternative E6 in the MES-model. Assumptions of biomass growth and crop yield are based on own empiric results from using biogas slurry for maize and beans alongside compost for cabbage and onion (Krause et al., 2016).

Figure S7: Biogas slurry taken from the outlet of a biogas digester constructed as pilot digester in Karagwe (own picture, March 2014).

In **scenario AM3**, the area cultivated with maize and beans is amended with so-called 'CaSa-compost'. Preparing CaSa-compost is tested in the project 'Carbonization and Sanitation' (CaSa), which acts as a case study to the present work (cf. main article). The area cultivated with vegetables, both cabbage and onion, is amended with standard compost. In addition, urine is used as mineral fertilizer for all crops. Standard and CaSa-composting processes are modelled as part of the present AES-model (Supplementary 2.6.I and 2.6.II, respectively). According to Krause et al. (2015), CaSa-compost contains a mix of pasteurised human faeces, kitchen waste, harvest residues, terracotta particles, ash, and urine mixed with biochar. Biochar, which is available from cooking and from thermal sanitation is quantified in Krause and Rotter (2017) in alternative E4 as part of the MES-model and in alternative S3 in the MSS-model, respectively. Weights and volumes of urine and sanitized human faeces recovered from sanitation are also quantified in Krause and Rotter (2017) in alternative S3 in the MSS-model. Assumptions of biomass growth and crop yield are based on own empiric results from using CaSa-compost for maize and beans and standard compost for cabbage and onion (Krause et al., 2016).

The IPNM-strategy analysed in **scenario AM4** is generally comparable to that studied in AM3. The main difference is that, in AM4, yields estimated for total biomass and grains are lower compared to AM3. In AM4, the assumed biomass growth and crop yield are based on results from using standard compost described in Krause et al. (2016) *for all crops*. We did this, because results gained by using CaSa-compost in the local experiment have been remarkably high. However, the experiment lasted only for one season and an empiric *proof* of results is pending. It is therefore somehow speculative, to assume that such high results can be realized for both of the two cultivation periods per year and in the long run or for many consecutive seasons. Thus, with AM4 we introduced another *more conservative* scenario in comparison to AM3 but with the same assumptions in terms of fertilizer applications to land used as *msiri.*

Figure S8: CaSa-compost produced in pilot project of CaSa-project in Karagwe, TZ (own picture, March 2014).

Also, **scenario AM5** is comparable to AM3. However, in AM5, nutrients are supplied with a one-off large amendment of organic fertilizers and additional seasonal mineral inputs through urine application. This means that total composts prepared during one year are amended on one third of the cultivated land. In the process, standard compost and CaSa-compost are used for growing vegetables and maize/beans, respectively. This application is repeated every year and on a rotating basis. Through this practice, the whole area is amended with compost after three years. In contrast*,* the compost is applied to the same area every four years again. The assumed biomass growth and crop yield in AM5 are comparable to AM3.

Figure S9: Urine is collected and stored in a urine-diverting dry toilet (UDDT); storage lasts for minimum two months in order to successfully inactive pathogens (drawing from CaSa-project document, CC).

1.3. Method applied and basic organisation of computational work.

In the AES-model, we applied the **method of soil nutrient balances** (SNB). Essentially, we combined concepts and terminologies as introduced by Stoorvogel and Smaling (1990) and modifications of Stoorvogel et al. (1993), Smaling et al. (1996) and Lesschen et al. (2007). We further followed Van den Bosch et al. (1998) and divided the *full SNB* into a *natural balance* (NB) and a *partial balance* (PB). The NB comprises all immissions and emissions from and to the environment and the PB reflects the 'way of farming' and solely consists of organic and mineral fertilizer inputs and nutrient removals by food crops and harvest residues. After an exhaustive literature review, we selected those flows which were most relevant and quantifiable in the specific context (Table S27). Our specific modelling approach is summarized in the following paragraph and is also further described and visualised in the main article (Section 2.3. and Fig. 2).

The chosen **fertilization strategy** is based on (i) optimizing P-efficiency, (ii) avoiding over-fertilization with P, and (iii) avoiding under-fertilization with N. Hence, our model follows suggestions put forth by Buresh et al. (1997) and Eghball and Power (1999), stating that if the ratio of N/P of the crops' nutrient requirement is higher than the ratio of N/P in organic fertilizer, then organic matter should be used first to balance the P uptake of crops. Mineral fertilizer can also be used to meet crops' N requirements. In most of the scenarios in our model, the N/P of the crops' nutrient requirement is higher than N/P in organic fertilizers, thus $\frac{N}{P}_{mineral\ input} \geq \frac{N}{P}_{crops\ requirement} \geq \frac{N}{P}_{organic\ inputs}$ (Table S26).

Table S26: N/P-ratios in nutrient requirements of crops and in the soil amendments for the analysed scenarios (AM1-AM5).

	Crops' nutrient requirements	Organic input						Mineral input
		Compost (lab)	Compost (mod)	Biogas slurry (lab)	Biogas slurry (mod)	CaSa (lab)	CaSa (mod)	Urine
AM1	4.2	4.2	1.1	NA	NA	NA	NA	NA
AM2	4.4	4.2	2.9	2.1	3.1	NA	NA	9.0
AM3	3.7	4.2	3.1	NA	NA	1.9	2.6	9.0
AM4	4.2	4.2	2.9	NA	NA	1.9	2.5	9.0
AM5	3.7	4.2	3.1	NA	NA	1.9	2.6	9.0

To sum up: organic inputs such as standard compost, CaSa-compost, and biogas slurry are used to meet crop's primary requirements for P, to complement organic amendments, and to supply additional N. Stored urine is used as **a** liquid mineral fertiliser. Urine is known as a fast acting and rapidly available N-fertiliser, which is often diluted with water, e.g. in a ratio of 1:3 to 1:5 urine to water (Richert et al., 2010). Dilution is mainly done to avoid over-utilisation of urine and to reduce the odour. If urine is rather used neat, Richert et al. (2010) recommended applying the urine into a furrow or hole and to close the furrow/hole with soil afterwards. This can reduce N-losses through sub-surface volatilization. In order to restore soil P stocks efficiently, Buresh et al. (1997) further recommend either seasonal moderate applications of organic fertilizers or one-off large applications. The first recommendation is considered in scenarios AM1-4, the latter in scenario AM5, as described above.

Calculations were made through a **series of steps**. Here we briefly summarize the principle procedure and further elaborate the steps including the equations applied in Supplementary 2. The first step was to estimate the NB (Supplementary 2.1 and 2.2). Values of IN and OUT for the NB derive from literature (Table S27). Then, we calculated the total biomass production for PB, including crop yields and plant residues, and the respective total nutrient uptake by plants ($\mathrm{OUT}_{\mathrm{crops}}$; Supplementary 2.3). Grass carpeting and mulching with residues are considered local standard practices, and are therefore included as organic IN into 'PB I without fertilization' (Eq. S2). It follows, therefore, that PB I reflects the 'net nutrient requirements' of crops. Application of organic and mineral fertilizers are considered in 'PB II with organic fertilization' (Eq. S3), and 'PB III with organic *and* mineral fertilization' (Eq. S4), respectively. Organic and mineral INs are quantified based on the net nutrient requirements calculated in PB I (Supplementary 2.4). Finally, 'full SNB I with organic fertilization' (Eq. S5) and 'full SNB II with organic and mineral fertilization' (Eq. S6) are calculated.

$$\text{PB I} \stackrel{\text{def}}{=} \text{IN}_{carpeting} + \text{IN}_{mulching} - \text{OUT}_{\text{crops}} = \text{IN}_{2a} + \text{IN}_{2b} - \sum (OUT_{1a} + OUT_{1b} + OUT_2)$$

$$\stackrel{\text{def}}{=} \left|\text{nutrient requirement}_{crops}\right| \quad \text{Eq. (S2)}$$

$$\text{PB II} \stackrel{\text{def}}{=} \text{PB I} + \text{IN}_{compost} + \text{IN}_{CaSa-compost} + \text{IN}_{biogas\ slurry} = \text{PB I} + \text{IN}_{2c} + \text{IN}_{2d} + \text{IN}_{2e} \quad \text{Eq. (S3)}$$

$$\text{PB III} \stackrel{\text{def}}{=} \text{PB II} + \text{IN}_{urine} = \text{PB II} + \text{IN}_{1c} \quad \text{Eq. (S4)}$$

$$\text{SNB I} \stackrel{\text{def}}{=} \text{NB} + \text{PB II} \quad \text{Eq. (S5)}$$

$$\text{SNB II} \stackrel{\text{def}}{=} \text{NB} + \text{PB III} \quad \text{Eq. (S6)}$$

where IN is the nutrient input flows, OUT is the nutrient output flows, PB is the partial balance, NB is the natural balance, and SNB is the full soil nutrient balance.

In addition to the SNB, the AES-model also includes a preceding process, which is the **composting**. Here, different organic waste materials are mixed for the subsequent aerobic, bio-chemical decomposition. Two approaches to composting are depicted in the model: (i) the ‘standard composting’, which follows local practices and primarily includes harvest and kitchen residues (Supplementary 2.6.I), and (ii) the ‘CaSa-composting’, which is applied to jointly exploiting biochar, stored urine, sanitized faeces, and other organic residues (Supplementary 2.6.II). During composting, emissions to the natural environment occur, such as CO_2-, CH_3-, or N_2O-emissions, or P-leaching.

In aggregating the data, we assumed that all parameters were normally distributed and independent of variables (Laner et al., 2014). All mathematical operations are first carried out with an arithmetic mean value of ($\bar{x}$). To apply **error propagation statistics**, we calculate standard error (Δx), which derives from the standard deviation (σ) of the test series or data set, and the relative uncertainty (RU), which is defined as Δx in % of $\bar{x}$ (Brunner and Rechberger, 2004). Finally, *Gauss's law of error propagation* (Brunner and Rechberger, 2004; FAU physics, 2016) is applied, which differs for addition or subtraction (Eq. S7 and S8) and multiplication or division (Eq. S9 and S10).

If $y = c_1\,\bar{x}_1 + c_2\,\bar{x}_2 + \ldots + c_k\,\bar{x}_k$ with $c > 0$ (addition) and $c < 0$ (subtraction) then:

$$\Delta y = \sqrt{(c_1\Delta x_1)^2 + (c_2\Delta x_2)^2 + \ldots + (c_k\Delta x_k)^2} \quad \text{Eq. (S7)}$$

and $RU_y = \Delta y / \bar{y}$ Eq. (S8)

If $y = c\bar{x}_1^{m_1} \cdot \bar{x}_2^{m_2} \cdot \ldots \cdot \bar{x}_k^{m_k}$ with $m > 0$ (multiplication) and $m < 0$ (division) then:

$$RU_y = \sqrt{(m_1\,RU_1)^2 + (m_2\,RU_2)^2 + \ldots + (m_k\,RU_k)^2} \quad \text{Eq. (S9)}$$

and $\Delta y = RU_y \cdot \bar{y}$ Eq. (S10)

Note concerning data processing: if the standard deviation or the standard error is not available for a collected data set, then the uncertainty is set to be 30 % of mean value.

All calculations are performed in **Excel**. Data collection, data evaluation, and calculations of $\dot{m}$ for all scenarios are combined in one file comprising various **spreadsheets** including:

- Summary of data on *process values,* collected from literature, such as transfer coefficients (TC) for nutrients during composting process, emissions after application of organic and mineral fertilisers, etc. (Table S32);
- Summary of data on *material values,* collected from literature, such as compositions of composts, densities of component materials, nutrient concentrations in kitchen waste, harvest products, and fertilisers, etc. (Table S32);
- Summary of *context specific data*, collected from the partner organisation and via expert judgement, such as size of cultivated land, fate of residual matter from harvesting of main crops, etc. (Table S32);
- Summary of *empiric data*, collected in a field experiment on the local Andosol using various soil amenders including those relevant for the present analysis, such as total above ground biomass production, yields of marketable products, yields of harvest residues, etc. (Table S32);
- Summary of *data for determining the NB* of the SNB, collected from literature and calculated (Table S27);
- Summary of *data on crop specific yields of and nutrient concentrations* in harvest products compiled from results of our own field experiment (see above) and values collected from literature. (Table S32);

- Calculations of $\dot{m}$ related to SNB on separate spreadsheets for each sub-scenario AM1 to AM5; each spreadsheet is structured in two parts:
    1. 'Material and process values', comprising selected values from data collection, which are required for the calculations in this sheet (e.g. yields of and concentrations in harvest products, distribution of harvest residues, nutrient TCs for composting, etc.).
    2. 'Calculated material and nutrient flows', comprising calculations of all $\dot{m}_{input}$ and $\dot{m}_{output}$ of the PB on layers G, C, N, and P.
- Summaries and comparisons of results from the four scenarios, e.g. yields, fertiliser usage and application rates, estimated flows referring to the partial, natural, and full SNB, etc.
- Summary of selected plausibility criteria for crosschecking estimated values from our model with reliable data from literature sources.
- Diagrams presenting results.

1.4. Assumptions and simplifications in the AES-model.

Across the five scenarios, we took the following basic assumptions to simplify modelling:

- Local agriculture and crop cultivation is **rain-fed only**, and no irrigation is applied.
- Crops are **intercropped in lines**. Every season the arrangement of cropping lines on the plot is **rotated**.
- **Beans** are not included in the PB of N. As legume plants, beans take up N from the atmosphere. 100 % of N taken up by beans is assimilated from the air.
- 50 % of the total N contained in the total biomass of beans would be available next season through **BNF**.
- BNF is equally distributed to the whole *msiri* because beans are intercropped and crop positions rotate on the plot. The N-input through BNF to a certain crop is proportional to the share of land cultivated with that crop.
- Residues and grasses are used for **mulching** and **carpeting**, respectively, whereby matters are equally applied to the whole *msiri*. Thus, nutrient inputs are also evenly distributed on the total area.
- Due to the present semi-arid, tropical savannah climate, with year-round elevated temperatures, **composting** lasts for three to six months, or approximately one season (Landon, 1991).
- Compost produced in one season, is available in the next season. *Vice versa*, compost used in the present season was produced in the previous season. The amount of compost *produced* and that of compost *used* are thus comparable in each season, and defined as equivalent before the background that our model is static, not dynamic.
- **Application of both composts** is done once per year and, thus, the total amount of compost needed to cover the nutrient demands of crops in two cultivation periods is applied.
- According to Finck (2007), **100 % of the P contained in compost** is available for plants *in the long-run*. Hence, in the real-world, the demand of crops growing in a certain season will be covered from several soil amendments that had been applied during previous seasons. In our static model, however, compost applied in one year computationally meets nutrient demands of crops grown during the same year.
- **Application of biogas slurry** is done every season. In our static model, the application is depicted as an annual input of biogas slurry per square meter. In the real-world, however, application can be done in several doses, which should follow the different phase of nutrient requirements during plant growth. For maize, for example, nutrient demands are highest in the period between day 28 and 56 (weeks 4 to 8) after sowing (KTBL, 2009).
- **Application of urine** as mineral input is modelled following comparable assumptions to fertilizing with biogas slurry. Simplified static application of urine is modelled per year and per square meter.
- Nutrient inputs added by **seeds** are not considered.
- Most **flows of the NB** are assumed based on literature using data of studies in a comparable specific context. Only the BNF is calculated based on bean production and thus varies across scenarios.
- Soil and nutrient losses through **wind and water erosion** are not considered.

Table S27: Commented list of material flows and assumptions of SNB in AES-model.

Flow name		Subdivision		Information derived from literature review	Sources	Assumptions for the present study and comments on integration in system analysis
				Input flows of the PB		
IN1	Mineral fertilizer	a	Synthetic fertilizer	Synthetic fertilizers are used on <1 % of the planted land in Kagera; no area being fertilized in Karagwe; farmers of Mavuno don't use synthetic fertilizers because of applied organic farming practice.	Mavuno, 2015; Tanzania, 2012	• Not considered.
		b	Ash	In Karagwe, ash is mainly deposited in heaps or thrown into pit latrines; sometimes used as reaction to declining soil fertility or to control pests. Farmers of Mavuno use ashes mainly for composting.	Baijukya et al., 1998; EfCoiTa, 2013; Mavuno, 2015; Rugalema et al., 1994	• Not considered as sole mineral input. • Ashes, from cooking and from burning harvest residues are considered as compost additive (→ IN2c or IN2d). • Available quantities from prior studies (Krause and Rotter, 2017).
		c	Urine	Can be considered as mineral fertilizer input.	Richert et al., 2010	• Urine considered as mineral fertilizer in addition to organic fertilizer to balance N-demand of crops. • Available quantities from prior studies (Krause and Rotter, 2017).
IN2	Organic inputs	a	Grass carpet	One of main sources of organic fertilization in Karagwe. In most cases, grasses derived from grassland surrounding the homestead.	Baijukya et al., 1998; Tanzania, 2012	• Grasses considered as import material flow to the AES. • Share of residues used for burning estimated through expert judgement (Table A.5). • N- and P-recycling rates assumed based on collected data.
		b	Mulching with crop residues	One of main sources of organic fertilization in Karagwe.	Baijukya et al., 1998; Tanzania, 2012	• Total quantity of available crop residues from the model. • Share of residues used for mulching estimated through expert judgement (Table A.5). • N- and P-recycling rates assumed based on collected data.
		c	Standard compost	About 78 % of the farmers applying fertilizer in Kagera use organic fertilizer. However, compost is applied on only 5 % of the planted land in sum of both cultivation periods. Increasing number of farmers at Mavuno use standard compost as promoted by agricultural technicians.	Mavuno, 2014; Tanzania, 2012	• Production of compost from various available organic wastes as part of the model. • Composition of compost based on local practice (Krause et al., 2015).
		d	CaSa-compost	In the past, human excreta contributed to farm-scale nutrient recycling before implementation of pit latrines; e.g. it is common for farmers to deposit human excreta on each stool of banana on a rotating basis. Nowadays, a pilot project in Karagwe focuses on recovery of these resources through EcoSan approaches.	Baijukya et al., 1998; Krause et al., 2015; Rugalema et al., 1994	• Production of CaSa-compost from various available organic wastes as part of the model. • Composition of CaSa-compost based on practice in CaSa-project (Krause et al., 2015). • Quantities of treated toilet waste and nutrient contents from prior studies (Krause and Rotter, 2017).
		e	Biogas slurry	Available for households possessing a BiogaST-digester.	Krause et al., 2015	• Available quantity of biogas slurry produced per household and nutrient content in biogas slurry from prior studies (Krause and Rotter, 2017).
		f	Manure	In Karagwe, 15 % of household possess cattle and usually less than five animals. Hence, minor use of manure. Especially structural poor households practise farming without animal keeping.	Baijukya et al., 1998; Rugalema et al., 1994; Tanzania, 2012	• Not considered.

				Input flows of the NB		
IN3	Atmospheric deposition	a	Wet (rain)	Related to precipitation; including N-fixation through lightening and formed NO_x dissolved in rainwater.	Lesschen et al., 2007	• Considered and estimated from mean value of literature data and own calculation after Lesschen et al., 2007 with an assumed mean annual precipitation of 900 dm^3 m^{-2}.
		b	Dry (dust)	Related to Harmattan dust; only relevant in West Africa, hence not relevant in the specific context.	Lesschen et al., 2007 (Fig. 1)	• Not considered.
IN4	Biological nitrogen fixation (BNF)	a	Symbiotic	From leguminous species; BNF of beans is ~50 % of the total N taken up by the plant in above-ground biomass.	Baijukya et al., 1998; Lesschen et al., 2007; Stoorvogel et al., 1993	• Beans are only legume crop in the AES-model. • 50 % of N in total harvest product of beans accounted as BNF in the NB • N-uptake of beans excluded in the PB for N, because N derived from atmosphere.
		b	Non-symbiotic	From rainfall and N-fixing trees.	Lesschen et al., 2007 (Eq. 2)	• Mean value of results from Baijukya et al., 1998 and own calculations with formula in Lesschen et al., 2007.
		c	Non-symbiotic	N fixation by cyanobacteria as an important process in soils under wetland rice production.	Lesschen et al., 2007	• Not considered.
IN5	Sedimentation	a	Irrigation water	In Kagera, 0.8 % of the total land used for agriculture is irrigated, mainly for vegetables and only in the short rainy season. Local agriculture mainly rain-fed.	Tanzania, 2012	• Not considered.
		b	Sedimentation	erosion as input; see Out 5.		• Not considered.
IN6	Subsoil exploitation			Considered especially important in agroforestry systems.	Van den Bosch, 1998	• Not considered.
				Output flows of the PB		
OUT 1+2	Harvest product			Total above ground biomass at time of harvesting including food products (OUT1a, b) and crop residues (OUT2a-d).		• Selected crops: maize, beans, onion, cabbage. • Yield estimations for all crops depend on fertilization. • Yield estimations based on literature review and own experiments (see Table A.3)
OUT1	Food products	a	Self-consumption	Food crops for consumption within farming household; nutrients remain on the farm and are potentially available for recycling through MSS.	Baijukya et al., 1998; Rugalema et al., 1994	• Average share of harvest products used for own consumption available from unpublished pre-studies (see Table A.1). • Nutrient content determined through data collection.
		b	Sold to market	Food crops for selling at the market for income generation; nutrients being exported from the farmland	Baijukya et al., 1998; Rugalema et al., 1994	• Average share of harvest products used for selling available from unpublished pre-studies (see Table A.1). • Nutrient content determined through data collection.
OUT2	Crop residues	a	Burnt	Burning of agricultural residues, which are removed from the field.	Lesschen et al., 2007; Mavuno, 2015	• 2 % of harvest residues are burnt; • 100 % of C and N in burnt matter emitted when burning, 100 % of P is recyclable with ashes → IN1c and IN2d; • Further emissions calculated based on Aalde et al., 2006.
		b	Mulching	Agricultural residues remaining on the field as cover material; important practice to control evaporation of soil moisture in dry season.	Baijukya et al., 1998; Mavuno, 2015; Rugalema et al., 1994	• 47 % of harvest residues are used for mulching → IN2a.
		c	Composting	Agricultural residues taken from the field and used for composting.	Mavuno, 2015	• 41 % of harvest residues are used for mulching → IN2b or IN2c.
		d	Exported	Given to animals as fodder, used as construction materials, dumped, sold, etc..	Mavuno, 2015	• 10 % of harvest residues are exported from AES; • Nutrients and carbon accounted as export flow from farmland.

Output flows of the NB						
OUT3	Leaching			Leaching of N and K can be an important outflow, which is quantified with regression models.	Lesschen et al., 2007	• Mean value of data collected from literature review.
OUT4	Gaseous losses	a	Denitrification	Takes place under anaerobic conditions, e.g. on loamy soils under wet climate; mainly N_2O.	Lesschen et al., 2007	• Mean value of data collected from literature and own calculation after Eq. (5) in Lesschen et al., 2007.
		b	Volatilisation	Important in alkaline environments but is neglected on acidic soils.	Baijukya et al., 1998; Lesschen et al., 2007	• Not considered.
OUT5	Soil erosion	a b	With wind With water	Baijukya et al., 1998 'considered (erosion) not important in perennial homegardens'; lack of sufficient data on slopes and erosion sensitivity of local soil; farmers in Karagwe apply erosion control measures such as trenches, mulching, intercropping with cover-crops, and agroforestry to control soil erosion; Mavuno strongly emphasizes implementation of erosion control measurements.	Baijukya et al., 1998; Mavuno, 2014; Tanzania, 2012	• Not considered.
OUT6	Human excreta		Urine and faeces ending up in deep pit latrine	Since implementation of pit latrines in 1940s, urine and faeces are deposed in pit latrine, where nutrients are stored unavailable.	Baijukya et al., 1998; Rugalema et al., 1994; Smaling et al., 1996	• Considered as recycling flow with IN1c and IN2d.

Non-common abbreviations: AES: agroecosystem; BiogaST: project 'Biogas support for Tanzania'; CaSa: project 'Carbonization and Sanitation'; EcoSan: ecological sanitation; EfCoiTa: project 'Efficient cooking in Tanzania'; MES: micro energy system; MSS: micro sanitation system; NB: natural balance; PB: partial balance; SNB: soil nutrient balance

Supplementary 2. SPECIFIC EQUATIONS APPLIED FOR MODELLING

In addition to the principle equations (Eq. A.1-A.6), we applied a set of equations which are explained in this chapter. In sum, equations are applied for following purposes:

1. To determine the NB for *msiri* (S2.1 and 2.2);
2. To determine the PB for *msiri*, (S2.5), which is based on:
   a. Quantifying possible yields without fertilisation (AM1) and with fertilisers (AM3-AM5) (Section S2.3),
   b. Quantifying the amounts of organic and mineral inputs (S2.4);
3. To model the composting process for two different kinds of compost (S2.6).

Note: Material flows are generally abbreviated following the concept of SNB with some adoptions specifically for the present model (Table A.3. and Table 5 in the main article). The layer of modelling is indicated by the first index after the variable (e.g. $OUT1_P$ *as flow of P in OUT1).*

2.1. Output flows of the natural balance.

The $\dot{m}_{output}$ of the NB includes losses through **leaching** of liquids and dissolved nutrients ($OUT3$) along with **gaseous losses** through denitrification ($OUT4a$) which are quantified through literature review (Table S27). From the data collected, we deduced mean values of $\dot{m}_{OUT_3}$ and $\dot{m}_{OUT_{4a}}$ in kg ha^{-1} yr^{-1}, which are extrapolated by applying:

$$OUT3 \ = \dot{m}_{OUT_3} \cdot area_{msiri} \qquad \text{Eq. (S11)}$$

$$OUT4a = \dot{m}_{OUT_{4a}} \cdot area_{msiri} \qquad \text{Eq. (S12)}$$

Both $\dot{m}_{output}$ are calculated for the layer of N only.

2.2. Input flows of the natural balance.

The $\dot{m}_{input}$ of the NB includes **atmospheric wet deposition** ($IN3a$) and **asymbiotic N fixation** ($IN4b$), which are quantified by reviewing literature (Table S27). Literature provided general values for $\dot{m}_{IN_{3a}}$ and $\dot{m}_{IN_{4b}}$ in kg ha^{-1} yr^{-1}, which are extrapolated by applying:

$$IN3a = \dot{m}_{IN_{3a}} \cdot area_{msiri} \qquad \text{Eq. (S13)}$$

$$IN4b = \dot{m}_{IN_{4b}} \cdot area_{msiri} \qquad \text{Eq. (S14)}$$

The $IN3a$ is calculated for layers N and P whilst $IN4b$ is only relevant to the layer of N.

In addition, N-input through **symbiotic BNF** ($IN4a$) is calculated. Thereby, we assumed that 50 % of the N-uptake of the plant, distributed to the bean ($OUT1_{N,beans}$), to straw ($OUT2_{N,beans,straw}$), and to leaves ($OUT2_{N,beans,leaves}$), contributes to NB:

$$IN4a = 0.5 \ \cdot (OUT1_{N,beans} + OUT2_{N,beans,straw} + OUT2_{N,beans,leaves}) \qquad \text{Eq. (S15)}$$

2.3. Output flows of the partial balance.

The $\dot{m}_{output}$ of the PB include (i) total biomass production, (ii) nutrient uptake of selected crops, (iii) gaseous emissions from the application of fertilizers, and (iv) gaseous emissions from burning agricultural residues.

2.3.1. Biomass production

The total biomass comprises food products (OUT1) and harvest residues (OUT2). Furthermore, food products are used to contribute to the food supply and incomer generation of the farming family. Therefore, we consider a share of food product harvested as being used for self-consumption (OUT1a) and the rest as being sold at local markets or to intermediaries (OUT1b). The respective distribution of total food products has been assessed during pre-studies of this work in 2010 and via questionnaire (Table S28).

Table S28: Use of the harvested food product.

Crop	Self consumption ($frac_{SC}$)	Sold to market
Maize	66%	34%
Beans	38%	62%
Onion	100%	0%
Cabbage	100%	0%

Note: In the main article, only results for the total harvest of food products (OUT1) are presented and discussed. Further discussion of results for OUT1a and OUT1b is included in the synthesis of the dissertation of Ariane Krause and discussed in the context of food security for smallholders in Karagwe[3].

The **total $\dot{m}_{output}$ of food products** (OUT1) is first calculated for each crop (Eq. S16) and then summed up for all four crops (Eq. S17).

$$\mathrm{OUT1}_{G,maize} = MF \cdot LU_{maize} \cdot Y_{FP,maize}\ 1000 \qquad \text{Eq. (S16)}$$

Exemplarily shown for determining the total production of food products of maize ($\mathrm{OUT1}_{G,maize}$ in kg yr^{-1}) by using the model factor (MF), the factor describing land used for maize cultivation (LU_{maize}) and the specific yield of food products for maize ($Y_{FP,maize}$ in t ha^{-1} season^{-1}). Flows of OUT1 for the other crops are calculated accordingly by using the crop-specific values for LU and Y.

$$\mathrm{OUT1}_{G,total} = \mathrm{OUT1}_{G,maize} + \mathrm{OUT1}_{G,beans} + \mathrm{OUT1}_{G,onion} + \mathrm{OUT1}_{G,cabbage} \qquad \text{Eq. (S17)}$$

Subsequently, food products are distributed to OUT1a and OUT1b by using the variable indicating the crop-specific fraction of the harvest used for self-consumption ($frac_{SC,maize}$) and the following equations:

$$\mathrm{OUT1a}_{G,maize} = \mathrm{OUT1}_{G,maize} \cdot frac_{SC,maize} \qquad \text{Eq. (S18)}$$

$$\mathrm{OUT1b}_{G,maize} = \mathrm{OUT1}_{G,maize} - \mathrm{OUT1a}_{G,maize} \qquad \text{Eq. (S19)}$$

Exemplarily shown for maize; the flows OUT1a and OUT1b for the other crops can be calculated accordingly by using the crop-specific values for $frac_{SC}$ (see Table S28).

The total $\dot{m}_{output}$ **of harvest residues** (OUT2) is calculated in the same way as OUT1. Thus, we applied Eq. S16 and S17 but with crop-specific values for yields of harvest residues ($Y_{HR,maize}$ in t ha^{-1} season^{-1}) (Table S32).

Finally, we consider the **use of harvest residues** according to local practices:

$$\mathrm{OUT2b}_{G} = \mathrm{OUT2}_{G} \cdot frac_{mulching} \qquad \text{Eq. (S20)}$$

Exemplarily shown for harvest residues used for mulching ($\mathrm{OUT2b}_G$ in kg yr^{-1}) by using the total amount of available harvest residues ($\mathrm{OUT2}_G$) and the factor describing the use of harvest residues for mulching ($frac_{mulching}$). The other $\dot{m}_{output}$ for burnt, composted, or other purposes can be calculated accordingly by using, respectively, $frac_{burning}$, $frac_{composting}$, or $frac_{others}$.

Information on the fate of harvest residues has been collected through expert judgement (Mavuno, 2015) and is presented in Table S29. Residues are burnt (OUT2a), recycled to the AES by using them for mulching (OUT2b), composted (OUT2c), or exported (OUT2d). The fist flow is divided into emissions to the atmosphere ($\mathrm{OUT2a}_{emission}$) and ashes remaining after incineration ($\mathrm{OUT2a}_{ash}$). The $\mathrm{OUT2a}_{emission}$ is an *export flow* (see S2.3.IV) whilst $\mathrm{OUT2a}_{ash}$ is a *recycling flow* because ashes are added to the compost (see S2.4.). Flow OUT2d includes harvest residues that are dumped (outside the farmland), used as construction material, thrown in toilet, sold, etc.

[3] The dissertation titled 'Valuing wastes - An Integrated System Analysis of Bioenergy, Ecological Sanitation, and Soil Fertility Management in Smallholder Farming in Karagwe, Tanzania' will be published at *DepositOnce*, the repository for research data and publications of TU Berlin during 2018.

Table S29: Fate of the harvest residues determined through expert judgement (Mavuno, 2015).

Flow name	Use of residue	Unit	Mean	Error	Uncertainty
OUT2a	Burning	% FM	0.02	± 0.01	48%
OUT2b	Composting	% FM	0.41	± 0.07	16%
OUT2c	Mulching	% FM	0.47	± 0.07	14%
OUT2d	Others	% FM	0.10	± 0.03	27%

2.3.2. Nutrient uptake of crops

The total $\dot{m}_{output}$ **of N and P** contained in **food products and harvest residues** are calculated from the total production in the G-layer ($\mathrm{OUT1}_G$ and $\mathrm{OUT2}_G$, respectively) and by using the concentration (c) of nutrients in the products. Values of nutrient concentrations are based on data from literature and own results (Krause et al., 2016) (Table S32).

$$\mathrm{OUT1}_{N,maize} = \mathrm{OUT1}_{G,maize} \cdot c_{FP,maize,N} \qquad \text{Eq. (S21)}$$

Exemplarily displayed for N in total food product of maize ($\mathrm{OUT1}_{N,maize}$) with $c_{FP,maize,N}$ being the concentration of N in the total food product (FP) of maize in % (FM).

$$\mathrm{OUT2}_{N,maize} = \mathrm{OUT2}_{G,maize} \cdot c_{HR,maize,N} \qquad \text{Eq. (S22)}$$

Exemplarily displayed for N in total harvest residues of maize ($\mathrm{OUT2}_{N,maize}$) with $c_{HR,maize,N}$ being the concentration of N in the total harvest residues (HR) of maize in % (FM).

Then, total nutrient exports for all crops are estimated by applying Eq. 17 to layers N and P (e.g. $\mathrm{OUT1}_{N,total}$ or $\mathrm{OUT2}_{P,total}$). The total $\dot{m}_{output}$ of nutrients with harvest residues is further distributed among the several usages of the harvest residues by applying Eq. 20 to derive, for example $\mathrm{OUT2c}_{N,}$ or $\mathrm{OUT2b}_P$ for mulching or composting, respectively.

2.3.3. Gaseous emissions from fertiliser applications

When adding fertilizers on managed soils, volatilization, nitrification, and denitrification processes occur which lead to emissions of N_2O- and NH_3-gases (e.g. De Klein et al., 2006). Our model considers $\dot{m}_{output}$ of N through **N_2O- and NH_3-emissions after the addition of carpeting grasses, mulching material, urine, or biogas slurry**. N_2O- and NH_3-emissions are represented in the NB as flow OUT4a (Table S27). Furthermore, these emissions which reduce N-content in input matter, are accounted for by estimating a nutrient specific recycling-rate in percentage of the total nutrient input. For example, approximately 87 % of the total N contained in grasses used for carpeting will be recycled into the soil to be available for fertilization. The recycling-rate is considered in calculations of the $\dot{m}_{input}$ of the fertilizers required and are, thus, integrated in the equations explained in S2.4. Soil-borne CH_4 and CO_2 emissions from liming (De Klein et al., 2006) are not considered for simplification due to specific data gaps for the local soil. Possible **emissions after compost amendments are also not considered** because, according to Möller and Stinner (2009) NH_3-emissions depend on the NH_4-content. The latter is not commonly found in solid compost, which is also the case for both composts analysed (Krause et al., 2015).

2.3.4. Gaseous emissions from burning agricultural residues

Emissions from burning agricultural residues comprise CO_2, CO, CH_4, N_2O, and NO_x. These gaseous emissions are determined following Aalde et al. (2006), who provide emission factors (EF) in g kg^{-1} of DM of burnt residues.

$$\mathrm{OUT2a}_{G,emission,CO2} = \mathrm{OUT2a}_G \cdot c_{HR,DM} \cdot EF_{CO2} \qquad \text{Eq. (S23)}$$

Exemplarily displayed for CO_2-emissions ($\mathrm{OUT2a}_{emission,CO2}$) from burning harvest residues ($\mathrm{OUT2a}_G$) with $c_{HR,DM}$ being the concentration of dry matter (DM) in the total harvest residues (HR) and EF_{CO2} being the emission factor for CO_2. The other emissions are calculated accordingly with the specific EF, e.g. EF_{CO}, EF_{CH4}, etc.

Furthermore, we assumed that 100 % of total C and total N in the burnt matter is emitted to the atmosphere during incineration (Lesschen et al., 2007) whilst 100 % of P is recovered in ashes.

$\mathrm{OUT2a}_{C,ashes} = \mathrm{OUT2a}_{N,ashes} = 0$ Eq. (S24)

$\mathrm{OUT2a}_{P,ashes} = \mathrm{OUT2a}_{P}$ Eq. (S25)

2.4. Input flows of the partial balance.

To realise sustainable crop production and soil management, the total nutrient requirements of crops need to be balanced by inputs of nutrients. In our model, nutrients are provided with the following $\dot{m}_{input}$:

- Grass carpeting on the whole plot as standard practice in AM1-5,
- Mulching with crop residues on the whole plot as standard practice in AM1-5,
- Biogas slurry amendment for maize and beans in AM2,
- Compost amendment for vegetables in AM1-5 (in AM1 only for cabbage),
- CaSa-compost amendment for maize and beans in AM3-5, and
- Mineral fertilization with urine for all crops in AM2-5.

2.4.1. Organic input: carpeting and mulching

To reduce evapotranspiration of water in soil during the dry seasons and to avoid soil erosion by wind, it is a common local practice to cover the topsoil with (i) a carpet of grasses and (ii) a layer of mulch prepared from harvest residues. Carpeting with grasses is usually made at the end of the rainy season, before the dry season starts. Mulching is done at the time when agricultural residues accumulate, which is after harvesting or after drying of harvest products. Thus, mulching is usually done *before* planting and as part of the plot preparation while carpeting is done *after* planting and during the cultivation period. However, as our model is static, the time of application does not matter.

The total $\dot{m}_{input}$ of **carpeting material** ($IN2a_G$) is estimated based on an annual use of grasses in fresh-matter ($\dot{m}_{grass\ carpet,FM}$) and in kg ha^{-1} yr^{-1} as typical for the region (Table S32):

$IN2a_G = \dot{m}_{grass\ carpet,FM} \cdot area_{msiri}$ Eq. (S26)

We further assume that 100 % of P contained in grasses is available to growing plants ($IN2a_P$), and thus:

$IN2a_P = IN2a_G \cdot c_{grass,P}$ Eq. (S27)

With the amount of carpeting grasses applied in FM ($IN2a_G$) and the concentration of P in FM of grasses in % ($c_{grass,P}$).

However, $\dot{m}_{input}$ of N with carpeting ($IN2a_N$) is lower than the total N contained in the grasses because of gaseous emissions (S2.3.III). Following Larsson et al. (1998) and Schmidt (1997), we consider that 11.5 ± 3.0 % of the total N would be lost through NH_3-emissions. In addition, Larsson et al. (1998) and Möller and Stinner (2009) assume that on average, 1.6 ± 0.3 % of the total N is transferred to N_2O-emissions. Thus, in total, 87 ± 3 % of the total N contained in grasses or mulching material ($frac_{rec.,grass,N}$) is recycled, and thus available to plants. We recognize this with:

$IN2a_N = IN2a_G \cdot c_{grass,N} \cdot frac_{rec.,grass,N}$ Eq. (S28)

With the applied FM of grass used for carpeting ($IN2a_G$) and the concentration of N in FM of grasses in % ($c_{grass,N}$) and the fraction of N being effectively recycled to the AES from total N contained in the grasses ($frac_{rec.,grass,N}$).

The total $\dot{m}_{input}$ of **matter used for mulching** ($\mathrm{OUT2b}_G$) depends on yields of harvest residues (S2.3.I) and the share of agricultural residues used for mulching (Table S29).

To determine nutrient inputs with harvest residues, we consider gaseous losses from soil management in the same way as carpeting. First, we assume that 100 % of P contained in mulching material is recycled:

$\mathrm{IN2b}_P = \mathrm{OUT2c}_P$ Eq. (S29)

With the total input of P with mulching material ($\mathrm{IN2b}_P$) and the total P contained in harvest residues used for mulching ($\mathrm{OUT2c}_P$) (Table S29).

Then, $\dot{m}_{input}$ of N with mulching ($IN2b_N$) considers gaseous emissions after applying the matter (S2.3.III) and is thus reduced compared to the total N contained in harvest residues used for mulching ($OUT2b_N$):

$IN2b_N = OUT2b_N \cdot frac_{rec.,mulching,N}$ Eq. (S30)

With the total N applied with harvest residues used for mulching ($IN2b_N$) and the fraction of N being effectively recycled to the AES from total N contained in the harvest residues ($frac_{rec.,mulching,N}$).

We further assume that recycling-rates for N are comparable for carpeting and mulching.

$frac_{rec.,grass,N} = frac_{rec.,mulching,N}$ Eq. (S31)

In addition, we assume that materials used for carpeting and mulching are equally applied to the whole *msiri*. Thus, we assign $\dot{m}_{input}$ of nutrients to specific crops according to the LU, respectively, which becomes relevant to determine $\dot{m}_{input}$ of organic and mineral fertilizers.

2.4.2. Organic input: biogas slurry

According to our fertilization strategy (S1.3), the total amount of organic input is **based on crops' P-requirements** *after* carpeting and mulching. Hence in AM2, the total $\dot{m}_{input}$ of P with biogas slurry, for cultivating maize and beans, is calculated with:

$IN2e_{P,maize} = OUT1_{P,maize} + OUT2_{P,maize} - (IN2a_P + IN2b_P) \cdot LU_{maize}$ Eq. (S32)

Exemplarily displayed for maize; for beans, the calculation is done accordingly. With the factor indicating the land used for cultivating maize in % of the total *msiri* (LU_{maize}).

From this, the **crop-specific total $\dot{m}_{input}$ of biogas slurry** is deduced with:

$IN2e_{G,maize} = IN2e_{P,maize} / c_{biogas\ slurry,P}$ Eq. (S33)

Exemplarily displayed for maize; for beans, the calculation is done accordingly. With the concentration of P in FM of biogas slurry in % ($c_{biogas\ slurry,P}$).

Then, the **total $\dot{m}_{input}$ of biogas slurry** to land planted with maize and beans is calculated with:

$IN2e_{G,total} = IN2e_{G,maize} + IN2e_{G,beans}$ Eq. (S34)

Exemplarily displayed for the layer of G; the total nutrient input is determined accordingly for layers N and P.

The **total input of N considers N-losses** after the application of fertilizer. Following Amon et al. (2006) and Möller and Stinner (2009), we assume that 13.9 ± 2.2 % of the total N is lost through NH_3-emissions. In addition, 0.9 ± 0.2 % of the total N is lost through N_2O-emissions (*ibid.*) and 4.1 ± 1.5 % of the total N is lost through nitrate leaching (Prasertsak et al., 2001). Thus, in total, 81 ± 3 % of the total N contained in biogas slurry ($frac_{rec.,biogas\ slurry,N}$) is finally available to crops as $IN2e_N$. Given that beans derive N through BNF, we assume that the total N in biogas slurry can be consumed by maize plants ($IN2e_N = IN2e_{N,maize}$).

$IN2e_{N,maize} = IN2e_{G,maize} \cdot c_{biogas\ slurry,N} \cdot frac_{rec.,biogas\ slurry,N}$ Eq. (S35)

With the total amount of biogas slurry applied to the land planted with maize and beans ($IN2e_{G,maize}$), the concentration of N in FM of biogas slurry in % ($c_{biogas\ slurry,N}$), and the fraction of N being effectively recycled to the AES from total N contained in the biogas slurry ($frac_{rec.,biogas\ slurry,N}$).

Finally, we compare if $\dot{m}_{input}$ of biogas slurry required can be covered with the available residues from the MES: $IN2e_{G,total} \leq \dot{m}_{biogas\ slurry\ available}$. If $IN2e_{G,total} \geq \dot{m}_{biogas\ slurry\ available}$, then $IN2e_{G,total}$ is manually decreased to $IN2e_{G,total} = \dot{m}_{biogas\ slurry\ available}$.

2.4.3. Organic input: standard compost

To determine **$\dot{m}_{input}$ of P with standard compost** we also consider P-requirements of the vegetables *after* carpeting and mulching:

$$IN2c_{P,cabbage} = OUT1_{P,cabbage} + OUT2_{P,cabbage} - (IN2a_P + IN2b_P) \cdot LU_{cabbage} \quad \text{Eq. (S36)}$$

Exemplarily displayed for cabbage; calculations for onion completed accordingly with the LU-factor for cabbage in % of the total *msiri* ($LU_{cabbage}$).

From this, the $\dot{\boldsymbol{m}}_{\boldsymbol{input}}$ **of standard compost to cabbage or onion** is deduced with:

$$IN2c_{G,cabbage} = IN2c_{P,cabbage}/c_{compost,P} \quad \text{Eq. (S37)}$$

Exemplarily displayed for cabbage; calculations for onion accordingly. With concentration of P in standard compost in % of FM ($c_{compost,P}$).

Then, the **total** $\dot{\boldsymbol{m}}_{\boldsymbol{input}}$ of standard compost to land planted with cabbage and onion is calculated:

$$IN2c_{G,total} = IN2c_{G,cabbage} + IN2c_{G,onion} \quad \text{Eq. (S38)}$$

Note: standard compost is only applied to cabbage in AM1, and to cabbage *and* onion in AM2-AM5.

As already explained (S2.3.III), we do not consider any **N-losses** after the amendment of compost. Hence:

$$IN2c_{N,cabbage} = IN2c_{G,cabbage} \cdot c_{compost,N} \quad \text{Eq. (S39)}$$

Exemplarily displayed for cabbage; calculations for onion completed accordingly with concentration of N in standard compost in % of FM ($c_{compost,N}$).

Finally, we compare whether $\dot{m}_{input}$ of the standard compost required can be covered with compost produced: $IN2c_{G,total} \leq \dot{m}_{compost\ available}$. If $IN2c_{G,total} \geq \dot{m}_{compost\ available}$, then $IN2c_{G,total}$ is manually decreased to $IN2c_{G,total} = \dot{m}_{compost\ available}$.

2.4.4. Organic input: CaSa-compost

The total $\dot{m}_{input}$ of CaSa-compost ($IN2d_{G,total}$) to maize and beans is determined in a comparable way as described above for biogas slurry. However, for CaSa-compost we also assumed that no N-losses occur after the soil amendment so that 100 % of the total N contained in CaSa-compost are plant-available. Thus, the calculation of $IN2d_N$ followed Eq. S39 rather than Eq. S35 with concentration of N in CaSa-compost in % of FM ($c_{CaSa-compost,N}$).

2.4.5. Mineral input: urine application

To balance N after organic amendments, urine is used as an additional mineral fertilizer input. Associated with the use of urine as fertilizer, N-losses are assumed to be comparable to those occurring when using synthetic mineral fertilizers. Ammonia volatilisation after fertilisation with urine is thus assumed to be 7.3 ± 1.7 % of the total N in urine (Jönsson, 2002; Prasertsak et al., 2001; Rodhe et al., 2004), whilst N_2O emissions are 0.9 ± 0.2 % of total N (Amon et al., 2006; Möller and Stinner, 2009). In addition, 4.1 ± 1.5 % of the total N is lost through nitrate leaching (Prasertsak et al., 2001). Thus, in total, 88 ± 2 % of the total N contained in urine ($frac_{rec.,urine,N}$) is finally available to crops as $IN1c_N$. Because crops have different nutrient demands, the model determines application rates of urine ($IN1c_G$) [in $dm^3\ yr^{-1}$] separately for the areas of maize, beans, cabbage and onions respectively. However, the N-demand determined for the area planted with maize and beans is equivalent to N-demand of maize because beans are legume plants, performing BNF.

$$IN1c_G = \frac{\left(IN2e_N - OUT1_{N,maize} - OUT2_{N,maize} + (IN2a_N + IN2b_N + IN4a_N) \cdot LU_{maize}\right) \cdot 1000}{c_{urine,N} \cdot frac_{rec.,urine,N}} \quad \text{Eq. (S40)}$$

Exemplarily displayed for the area planted with maize and beans in scenario AM2. With N in biogas slurry applied ($IN2e_N = IN2e_{N,maize} + IN2e_{N,beans}$; N-demand for food products ($OUT1_{N,maize}$) and harvest products ($OUT2_{N,maize}$); N-inputs with carpeting ($IN2a_N$), mulching ($IN2b_N$) and BNF ($IN4a_N$); LU-factor for maize in % of the total *msiri* (LU_{maize}), the concentration of N in fresh matter of urine in kg dm^{-3} ($c_{urine,N}$); and the fraction of N being effectively recycled to the AES from total N contained in the urine ($frac_{rec.,urine,N}$).

Then, total $\dot{m}_{input}$ of N and P are determined by using the concentration of nutrients in urine. For N, a N losses are considered once again; respectively the fraction of N recycled to the AES is applied:

$$IN1c_N = IN1c_G \cdot c_{urine,N} \cdot frac_{rec.,urine,N} \quad \text{Eq. (S41)}$$

$$IN1c_P = IN1c_G \cdot c_{urine,P}$$ Eq. (S42)

2.5. Synthesis: calculating the partial balances and the full soil nutrient balances.

In more detail as compared to the general equations presented in S1.3, the nutrient balances are finally estimated as follows.: Grass carpeting and mulching with residues are considered local standard practices and are therefore included as organic IN into 'PB I without fertilization' (Eq. S2). It follows, therefore, that PB I reflects the 'net nutrient requirements' of crops. Application of organic and mineral fertilizers are considered in 'PB II with organic fertilization' (Eq. S3), and 'PB III with organic and mineral fertilization' (Eq. S4), respectively. Organic and mineral INs are quantified based on the net nutrient requirements calculated in PB I (S2.4). Finally, 'full SNB I with organic fertilization' (Eq. S5) and 'full SNB II with organic and mineral fertilization' (Eq. S6) are calculated.

The net nutrient requirements, or 'PB I without fertilization' are in all scenarios:

$$PBI_N = \frac{IN2a_N + \mathrm{IN2b}_N - \mathrm{OUT1}_{N,maize} - \mathrm{OUT2}_{N,maize} - \mathrm{OUT1}_{N,onion} - \mathrm{OUT2}_{N,onion} - \mathrm{OUT1}_{N,cabbage} - \mathrm{OUT2}_{N,cabbage}}{0.125\ ha}$$ Eq. (S43)

$$PBI_P = \frac{IN2a_P + \mathrm{IN2b}_P - \mathrm{OUT1}_{P,total} - \mathrm{OUT2}_{P,total}}{0.125\ ha}$$ Eq. (S44)

The PB II with organic fertilization in scenario AM1 is:

$$PBII_N = PBI_N + \frac{\mathrm{IN2c}_{N,total}}{0.125\ ha}$$ Eq. (S45)

$$PBII_P = PBI_P + \frac{\mathrm{IN2c}_P}{0.125\ ha}$$ Eq. (S46)

with $\mathrm{IN2c}_{N,total} = \mathrm{IN2c}_{cabbage}$ because the only organic input is compost applied to the land planted with cabbage.

Finally, the PB III with organic *and* mineral fertilization in scenario AM1 is comparable to PBII because no urine is used as a mineral input in AM1:

$$PBIII_N = PBII_N$$ Eq. (S47)

$$PBIII_P = PBII_P$$ Eq. (S48)

The PB II with organic fertilization in scenario AM2 is:

$$PBII_N = PBI_N + \frac{\mathrm{IN2c}_{N,total} + \mathrm{IN2e}_{N,total}}{0.125\ ha}$$ Eq. (S49)

$$PBII_P = PBI_P + \frac{\mathrm{IN2c}_P + \mathrm{IN2e}_P}{0.125\ ha}$$ Eq. (S50)

Finally, the PB III with organic *and* mineral fertilization in scenario AM2 is:

$$PBIII_N = PBII_N + \frac{\mathrm{IN1c}_{N,total}}{0.125\ ha}$$ Eq. (S51)

$$PBIII_P = PBII_P + \frac{\mathrm{IN1c}_{P,total}}{0.125\ ha}$$ Eq. (S52)

with $\mathrm{IN1c}_{\mathrm{N,total}} = \mathrm{IN1c}_{N,maize} + \mathrm{IN1c}_{onion\&cabbage}$

The PB II with organic fertilization in scenarios AM3-5 are:

$$PBII_N = PBI_N + \frac{\mathrm{IN2c}_{N,total} + \mathrm{IN2d}_{N,total}}{0.125\ ha}$$ Eq. (S53)

$$PBII_P = PBI_P + \frac{\mathrm{IN2c}_P + \mathrm{IN2d}_P}{0.125\ ha}$$ Eq. (S54)

with $\mathrm{IN2c} = \mathrm{IN2c}_{cabbage\&onion}$ and $\mathrm{IN2d} = \mathrm{IN2d}_{maize\&beans}$

Finally, the PB III with organic *and* mineral fertilization in scenarios AM3-5 are:

$$PBIII_N = PBII_N + \frac{\mathrm{IN1c}_N}{0.125\ ha}$$ Eq. (S55)

$$PBIII_P = PBII_P + \frac{\mathrm{IN1c}_P}{0.125\ ha}$$ Eq. (S56)

with $\mathrm{IN1c} = \mathrm{IN1c}_{maize} + \mathrm{IN1c}_{onion\&cabbage}$

2.6. Composting process.

In addition to those flows which are relevant for the SNB, we also modelled the composting process. For composting, various organic and organo-mineral materials are mixed (Figure S10 and S6) for subsequent bio-chemical metabolisms. Several decomposition and conversion processes result in the creation of the compost product as well as in gaseous (CO_2, N_2O, NH_3) and liquid (P-leaching) emissions that occur during composting. Based on literature values for specific emissions, we estimated TCs for nutrients, including 'N to gaseous emissions', 'N to compost', 'P to leachate', and 'P to compost' (Table S32). Compositions of compost are assumed based on local practices introduced in Krause et al. (2015) used for standard- and CaSa-composting. Characteristics of various materials used as well as of the products, such as water contents, nutrient concentrations, densities, etc. are collected from literature and complemented by own empiric data (Table S32). In scenarios AM3-5, both, standard composting *and* CaSa-composting, are part of the modelling. Hence, the total matter composed of harvest residues available for composting ($OUT2c$), ash from burning harvest residues ($\mathrm{OUT2a}_{ash}$), and kitchen waste are distributed to either of both composting practices by using defined TCs.

2.6.1. Standard composting

The standard compost, which is commonly prepared by local farmers, contains a mixture of fresh and dried grasses, ashes, and kitchen waste (Krause et al., 2015). In addition, water is added - if available - to improve the moisture content of the mixture. Topsoil is also added to introduce microorganisms. Composting is done in batches, which are often placed in a shallow pit in the ground and covered with soil and grasses to mitigate evaporation, and lasts for about three to six months. The figure S10 shows a flow diagram indicating how standard composting is depicted in our model with material flows indicated by arrows and the composting process as a box.

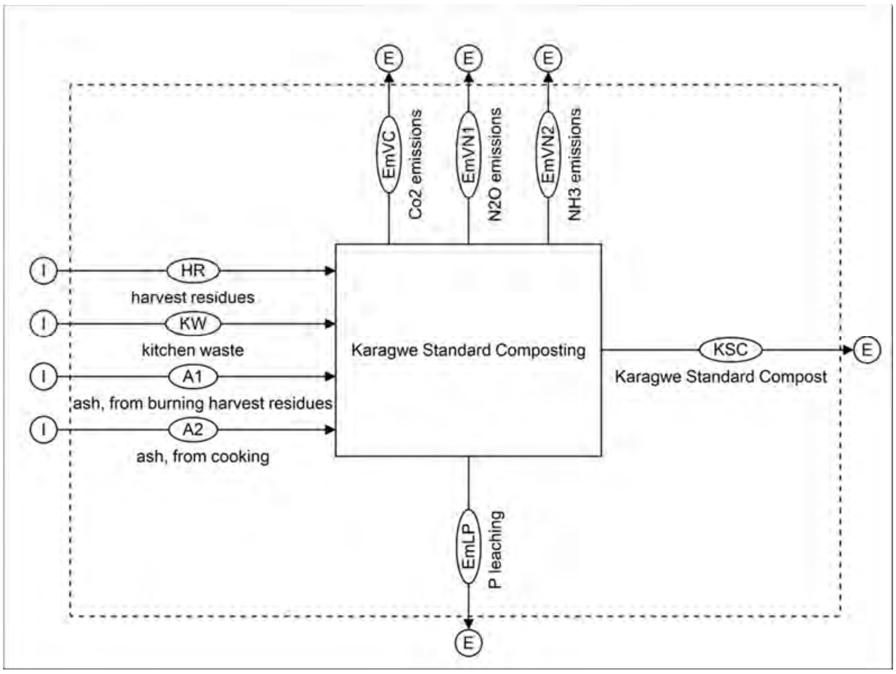

Figure S10: In- and output flows of materials to the Karagwe standard composting process.

$Compost_{G,input} = HR_G + KW_G + A1_G + A2_G$ Eq. (S57)

With $Compost_{G,input}$ as the sum of material used as input matter for composting, including harvest residues (HR), kitchen waste (KW), ash from burning harvest residues (S1), and ash from cooking (S2).

Ashes from cooking are only added to the composting in scenario AM1. Scenarios AM2-5 represent a shift in bioenergy technologies so that biogas digesters and burners (AM2) or microgasifiers (AM3-5) are used instead of three-stone fires (AM1). Hence, residues recovered from cooking include biogas slurry, which is used as direct organic input (IN2e), or biochar, which is used as an additive to CaSa-composting (S2.6.II). In scenarios AM3-5, CaSa-composting is more a part of the model, which requires distributing available input materials to both composting processes. Hence, in scenarios AM2 and AM3-5, Eq. S57 is adapted to Eq. S58 and S59, respectively.

$Compost_{G,input} = HR_G + KW_G + A1_G$ Eq. (S58)

$Compost_{G,input} = (HR_G + KW_G + A1_G) \cdot frac_{compost}$ Eq. (S59)

With $frac_{compost}$ as the TC of input matter available used for standard composting.

The production of compost ($Compost_{G,product}$) is also modelled by using TCs ($frac_{product,input,G}$) in all layers:

$Compost_{G,product} = Compost_{G,input} \cdot frac_{product,input,G}$ Eq. (S60)

Exemplarily shown on the layer G; equation is applied for layers C, N, P accordingly. $frac_{product,input,G}$ is the fraction of total input matter ($Compost_{G,input}$) being effectively transferred to the compost product ($Compost_{G,product}$) in % of $Compost_{G,input}$ on the layer G.

2.6.2. CaSa-composting

The CaSa-compost is made following the example of human-made *Terra Preta* soils, which are found in the Amazon Basin in South America, and are prominent for their outstanding fertility (Sombroek, 1966). Terra Preta production evolved centuries ago, and it is most probably the product of managing wastes and soil jointly. CaSa-composting, thus, includes co-composting of harvest residues, kitchen waste, ashes, biochar, pasteurised human faeces, ˜st ored urine, soil, and sawdust (Krause et al., 2015). Urine, as a locally available resource, is added (i) to increase the moisture of the compost (and thus to replace frequent watering of the compost pit) and (ii) to enrich CaSa-compost with N. According to local practices, after storing urine for a minimum one month in a UDDT, the stored urine is mixed with biochar and/or sawdust prior to addition. This is done to balance the high addition of N to the compost with additional C input because biochar and woody sawdust are rich in C. Balancing the ratio of N/C in the compost mixture is important to maintain the composting process. Commonly, terracotta particles are also added to improve the physical structure and water retention of the product. Additions of C or other nutrients are, however, of minor relevance for the input of terracotta, or brick particles and, thus, the respective input flow is not depicted in our model. In Karagwe, CaSa-composting is done in a similar way to the standard composting, which means it takes place in batches placed in a shallow pit in the ground, covered with soil and grasses to mitigate evaporation, and lasts for about three months. ˜The figure A.6 shows a flow diagram indicating how CaSa-composting is depicted in our model with material flows indicated by arrows and the composting process as a box.

Determining the sum of materials used as input matters for CaSa-composting ($CaSa - Compost_{G,input}$) is equivalent to Eq. S57, but all input flows are indicated by arrows on the left side of Fig. S11. The distribution of matters to CaSa-composting is done pursuant to Eq. S59 and with

$frac_{CaSa-compost} = 1 - frac_{compost}$ Eq. (S61)

Precisely, we assumed that 70 ± 7 % of $OUT2c$, $\mathrm{OUT2a}_{ash}$, or kitchen waste are utilized via CaSa-composting ($frac_{CaSa-compost}$) whilst 30 ± 3 % of $OUT2c$, $\mathrm{OUT2a}_{ash}$, or kitchen waste are utilized via standard composting ($frac_{compost}$).

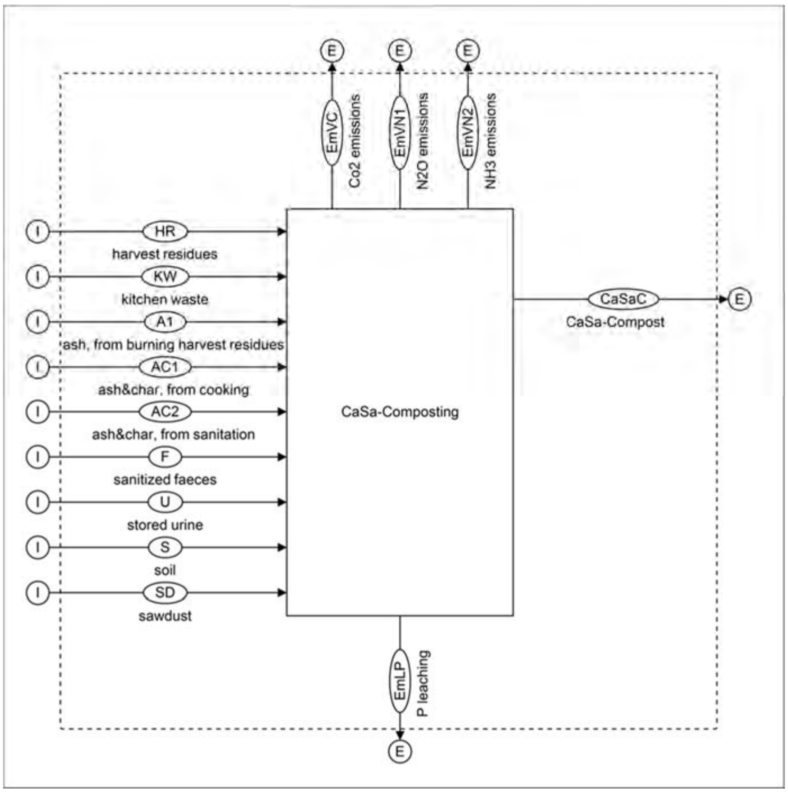

Figure S11: In- and output flows of materials to the CaSa-composting process.

The production of CaSa-compost ($CaSa\text{-}compost_{G,product}$) is also modelled by using TCs ($frac_{product,input,G}$) on all layers and pursuant to Eq. S60. Only for the transfer of C, are the calculations adapted because we assumed that 100 % of the C contained in biochar is transferred to the $CaSa\text{-}compost_{G,product}$.

Supplementary 3. ASSESSMENT OF EMISSIONS TO THE ENVIRONMENT

3.1. Assessment of greenhouse gas emissions to the atmosphere

The following emissions of greenhouse gases (GHG) are considered and determined in the model:

- From burning agricultural residues: CO_2, CO, CH_4, N_2O, and NO_x
- From carpeting and mulching: N_2O
- From standard composting and CaSa-composting: CO_2, N_2O
- From application of urine or biogas slurry: N_2O

We estimated the global warming potential (GWP) for the calculated GHG emissions in compliance with the procedure of the Intergovernmental Panel on Climate Change (IPCC) published by Myhre (2013). For this, we used GWP_{100}-factors[4] (Table S30) and multiplied these with the quantified material flows of emission components which are specifically relevant in terms of climate change.

We determined the total GWP of the farming system analysed for each scenario by summing up all emissions evaluated according to their GWP_{100}-factors. The total GWP is expressed in CO_2-equivalents per household and year (kg CO_2e hh^{-1} yr^{-1}).

[4] GWP for a time horizon of 100 years (Myhre et al., 2013).

Table S30: The GWP-factors used in this analysis; according to Myhre (2013).

Emission component	GWP_{100}-factor
CO_2	1
CO	2
CH_4	28
N_2O	265
NO_x	-11

The unit of the factor is kg CO_2e kg^{-1}.

3.2. Assessment of nutrient emissions to the hydrosphere

The following emissions determined are considered in the assessment of the eutrophication potential (EP):

- From burning agricultural residues: NO_x
- From carpeting and mulching: NH_3
- From standard composting and CaSa-composting: NH_3, P-leaching
- From the application of urine or biogas slurry: NH_3, N-leaching

In addition to the leaching of N and P, gaseous emissions of NO_x and NH_3 are also released into the atmosphere and contribute to nutrient transfers to the hydrosphere. Once in the air, the gases react with sulphuric acid and nitric acid and precipitate in the form of salt, which can easily be relocated to the pedosphere or hydrosphere. In addition, the salts dissolve easily in water, which can lead to an accumulation of nutrients in the water bodies and consequently to excessive growth of plants and algae (i.e. eutrophication).

We estimated the EP in compliance with the procedure of the Institute of Environmental Science at the University of Leiden published by Heijungs et al. (1992) and Guinée (2002). For this, we used the EP-factors (Table S31) and multiplied these with the quantified material flows of emission components, which are specifically relevant in terms of eutrophication. We determined the total EP of a scenario by summing up the single emissions assessed with the respective EP-factors. The total EP of the farming system is expressed in PO_4-equivalents per household per year (kg PO_4e hh^{-1} yr^{-1}).

Table S31: The EP-factors used in this analysis; according to Heijungs et al. (1992) and Guinée (2002).

Emission component	EP-factor
NO	0.13
NH_3	0.35
Total P (to water)	3.07
Total N (to water)	0.42

The unit of the factor is kg PO_4e kg^{-1}.

Supplementary 4. SHORT DISCUSSION

Firstly, we want to discuss, that soil and nutrient losses through wind and water erosion are not considered in our model. This is in line drawn by Baijukya et al. (1998), who also neglected soil erosion as a natural output flow when conducting SNB for *shamba* systems in the same local context. However, Lederer et al. (2015) found that erosion dominated nutrient exports from agricultural land in a district of Uganda. On average, N- and P-losses from arable land in Uganda are estimated with, respectively, 5-14 and 1.5-10 kg ha^{-1} yr^{-1} (Lederer et al., 2015; Nkonya et al., 2005; Wortmann and Kaizzi, 1998). In addition, Van den Bosch et al. (1998) report a possible range of 0-28 kg N ha^{-1} yr^{-1} in East Africa. Hence, erosion control measures like contour planting, catching water in trenches, etc. are absolutely necessary to avoid loss of topsoil. According to local expert judgment, most farmers in the community of MAVUNO are highly aware of soil erosion problems and efforts to implement countermeasures are widely adopted.

Furthermore, we acknowledge that we did not consider possible biochar-related effects when quantifying GHG emissions or nutrient leaching from the composting process. We rather assumed equal processes and emission factors for standard compost and biochar-containing CaSa-compost. We reason that existing scientific data on using biochar as a soil amendment are contradictory (cf. Mukherjee and Lal, 2014; Van Zwieten et al., 2015). Overall, available data expose: existing uncertainties in various areas, knowledge-gaps on underlying principles and mechanisms, and the admission that possible effects of biochar amendments are highly site-specific (*ibid.*). For these reasons, we judge that it is not yet possible to depict biochar effects in a model such as the one presented here.

Finally, we consider CO_2 emissions from composting or burning residues, and thus sourcing from biogenic material, pursuant to Gómez et al. (2006). We do this simply to obtain information to compare a possible decrease or increase in GHG emissions between the various IPNM strategies.

Supplementary 5. DATA COLLECTION OF MATERIAL AND PROCESS VALUES

In reference to Brunner and Rechberger (2004), data on material characteristics, such as moisture and nutrient content in biomass, crops, or fertilizer substrates, densities, etc., was collected through an extensive literature review, accessing case study documents, and prior research steps. This included information on process parameters including biomass and crop yields, emission factors, compost compositions, etc. (Table S32). Overall, we collected data for determining flows and stocks from various sources, including:

1. Primary data from case study projects, our own experiments, and previous studies, including household surveys, field tests, laboratory analysis, material flow modelling, etc.;
2. Secondary data, including literature reviews, statistics from private and public organizations, etc.; and
3. Estimations / experts judgments.

Table S32: List of material characteristics and other parameter values for the AES-model obtained from data collection and literature review provided with mean values ($\bar{x}$), standard error (Δx), relative uncertainty (RU), number of values collected to determine the mean value (n), data sources, and additional comments such as to the spatial context of the data.

Name	Unit	$\bar{x}$	Δx	RU	n	Sources	Comments
						Flows and parameters for the NB	
Atmospheric deposition - wet	kg N ha^{-1} yr^{-1}	6.4	± 3.2	50%	5	Calculation, based on Baijukya et al., 1998; Lesschen et al., 2007; Nkonya et al., 2005; Stoorvogel et al., 1993; Wortmann and Kaizzi, 1998	With assumed mean annual precipitation; Burkina Faso, Kagera, Karagwe, Uganda, Tanzania
Atmospheric deposition - wet	kg P ha^{-1} yr^{-1}	0.9	± 0.5	50%	5	Calculation, based on Baijukya et al., 1998; Lesschen et al., 2007; Nkonya et al., 2005; Stoorvogel et al., 1993; Wortmann and Kaizzi, 1998	With assumed mean annual precipitation; Burkina Faso, Kagera, Karagwe, Uganda, Tanzania
Symbiotic BNF with beans	kg N ha^{-1} yr^{-1}	14.0	± 2.3	17%	5	Calculation, based on Baijukya et al., 1998; Lesschen et al., 2007; Nkonya et al., 2005; Stoorvogel et al., 1993; Wortmann and Kaizzi, 1998	Burkina Faso, Kagera, Karagwe, Uganda, Tanzania
A-symbiotic nitrogen fixation	kg N ha^{-1} yr^{-1}	3.3	± 0.3	8%	3	Calculation, based on Baijukya et al., 1998; Lesschen et al., 2007	With assumed mean annual precipitation; Burkina Faso, Kagera, Karagwe, Uganda, Tanzania
Leaching	kg N ha^{-1} yr^{-1}	12.3	± 3.8	31%	4	Calculation, based on Baijukya et al., 1998; Lederer et al., 2015; Nkonya et al., 2005; Wortmann and Kaizzi, 1998	Only loss of N, no loss of P assumed Kagera, Karagwe, Uganda
Gaseous losses	kg N ha^{-1} yr^{-1}	15.7	± 4.3	27%	6	Calculation, based on Baijukya et al., 1998; Krause et al., 2016; Lederer et al., 2015; Lesschen et al., 2007; Nkonya et al., 2005; Wortmann and Kaizzi, 1998	Mean value from literature and own calculation after Eq. (5) in Lesschen et al., 2007; Kagera, Karagwe, Uganda
Mean annual precipitation	mm yr^{-1}	900	± 150	17%	8	Assumption, based on Baijukya et al., 1998; collected data by Mavuno, accessed through monitoring and evaluation report, 2014	Karagwe
Total N in rainfall	g N ha^{-1} mm^{-1}	4.9	± 2.5	51%	1	Lesschen et al., 2007	sub-Saharan Africa
Total P in rainfall	g P ha^{-1} mm^{-1}	0.6	± 0.5	83%	1	Lesschen et al., 2007	sub-Saharan Africa
Potential evapotranspiration	mm yr^{-1}	1,239	± 39	3%	2	Calculation, based on Baijukya et al., 1998	Kagera
						Crop yields	
Maize, harvest product	t ha^{-1} season^{-1}	33.7	± 3.4	10%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Maize, harvest product	t ha^{-1} season^{-1}	24.6	± 1.9	8%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Maize, harvest product	t ha^{-1} season^{-1}	22.3	± 2.3	10%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Maize, harvest product	t ha^{-1} season^{-1}	15.9	± 1.8	11%	5	Krause et al., 2016	Karagwe on un-amended soil
Maize, food product	t ha^{-1} season^{-1}	4.4	± 0.5	12%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Maize, food product	t ha^{-1} season^{-1}	3.2	± 0.4	12%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Maize, food product	t ha^{-1} season^{-1}	2.6	± 0.3	13%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Maize, food product	t ha^{-1} season^{-1}	1.1	± 0.1	13%	5	Krause et al., 2016	Karagwe on un-amended soil
Maize, food product	t ha^{-1} season^{-1}	1.2	± 0.03	3%	6	FAOSTAT, 2012; Krause et al., 2016; Smaling et al., 1993; Tanzania, 2012	Average on un-amended soil; Karagwe, Kagera, TZ
Maize, crop residues	t ha^{-1} season^{-1}	11.8	± 1.3	11%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Maize, crop residues	t ha^{-1} season^{-1}	8.1	± 1.0	12%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Maize, crop residues	t ha^{-1} season^{-1}	6.6	± 0.8	13%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Maize, crop residues	t ha^{-1} season^{-1}	3.8	± 0.4	11%	5	Krause et al., 2016	Karagwe on un-amended soil
Beans, harvest product	t ha^{-1} season^{-1}	13.8	± 1.6	12%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Beans, harvest product	t ha^{-1} season^{-1}	5.8	± 0.8	14%	5	Krause et al., 2016	Karagwe on soil amended with standard compost

Beans, harvest product	t ha^{-1} season^{-1}	4.0	± 0.5	14%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Beans, harvest product	t ha^{-1} season^{-1}	2.1	± 0.3	16%	5	Krause et al., 2016	Karagwe on un-amended soil
Beans, food product	t ha^{-1} season^{-1}	4.9	± 0.6	11%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Beans, food product	t ha^{-1} season^{-1}	1.6	± 0.4	26%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Beans, food product	t ha^{-1} season^{-1}	0.9	± 0.3	31%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Beans, food product	t ha^{-1} season^{-1}	0.4	± 0.1	27%	5	Krause et al., 2016	Karagwe on un-amended soil
Beans, food product	t ha^{-1} season^{-1}	0.7	± 0.1	14%	7	Baijukya et al., 1998; FAOSTAT, 2012; Krause et al., 2016; Mavuno, 2014; Smaling et al., 1993; Tanzania, 2012	Average on un-amended soil in Karagwe, Kagera, TZ
Beans, crop residues	t ha^{-1} season^{-1}	5.2	± 0.4	8%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Beans, crop residues	t ha^{-1} season^{-1}	1.6	± 0.3	19%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Beans, crop residues	t ha^{-1} season^{-1}	1.2	± 0.2	18%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Beans, crop residues	t ha^{-1} season^{-1}	0.8	± 0.2	27%	5	Krause et al., 2016	Karagwe on un-amended soil
Onion, harvest product	t ha^{-1} season^{-1}	22.4	± 2.8	12%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Onion, harvest product	t ha^{-1} season^{-1}	11.7	± 2.0	17%	5	Krause et al., 2016	Karagwe on un-amended soil
Onion, food product	t ha^{-1} season^{-1}	14.1	± 1.7	12%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Onion, food product	t ha^{-1} season^{-1}	5.9	± 1.5	25%	5	Krause et al., 2016	Karagwe on un-amended soil
Onion, food product	t ha^{-1} season^{-1}	3.9	± 1.0	26%	4	FAOSTAT, 2012; Krause et al., 2016; Tanzania, 2012	Average on un-amended soil in Karagwe, Kagera, TZ
Onion, crop residues	t ha^{-1} season^{-1}	1.1	± 0.4	35%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Onion, crop residues	t ha^{-1} season^{-1}	0.7	± 0.1	16%	5	Krause et al., 2016	Karagwe on un-amended soil
Cabbage, harvest product	t ha^{-1} season^{-1}	78.3	± 6.8	9%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Cabbage, harvest product	t ha^{-1} season^{-1}	71.4	± 9.8	14%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Cabbage, harvest product	t ha^{-1} season^{-1}	61.8	± 6.0	10%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Cabbage, food product	t ha^{-1} season^{-1}	50.8	± 5.4	11%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Cabbage, food product	t ha^{-1} season^{-1}	41.2	± 9.2	22%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Cabbage, food product	t ha^{-1} season^{-1}	36.0	± 5.3	15%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Cabbage, food product	t ha^{-1} season^{-1}	13.2	± 3.6	27%	3	FAOSTAT, 2012; Krause et al., 2016; Tanzania, 2012	Average on un-amended soil in Karagwe, Kagera, TZ
Cabbage, crop residues	t ha^{-1} season^{-1}	25.8	± 8.0	31%	5	Krause et al., 2016	Karagwe on soil amended with CaSa-compost
Cabbage, crop residues	t ha^{-1} season^{-1}	30.2	± 13.5	45%	5	Krause et al., 2016	Karagwe on soil amended with standard compost
Cabbage, crop residues	t ha^{-1} season^{-1}	25.8	± 8.0	31%	5	Krause et al., 2016	Karagwe on soil amended with biogas slurry
Moisture and nutrient concentrations in crops							
Maize, DM in biomass	% (in FM)	0.80	± 0.1	7%	3	KTBL, 2009; Krause et al., 2016	Germany, Karagwe
Maize, N in food product	% (in FM)	0.012	± 0.001	8%	6	Kimetu et al., 2008; KTBL, 2009; Krause et al., 2016; Lederer et al., 2015; Smaling et al., 1993	Germany, East Africa, Karagwe, Kenya, TZ, Uganda
Maize, N in crop residues	% (in FM)	0.005	± 0.0004	9%	3	KTBL, 2009; Krause et al., 2016; Smaling et al., 1993	Germany, Karagwe, East Africa, Kenya, TZ, Uganda
Maize, P in food product	% (in FM)	0.003	± 0.0002	6%	8	FAO, 1992; Kimetu et al., 2008; KTBL, 2009; Krause et al., 2016; Lederer et al., 2015; Smaling et al., 1993; Wadhwa and Bakshi, 2013	Asia, East Africa, generic, Germany, Karagwe, Kenya, TZ, Uganda
Maize, P in crop residues	% (in FM)	0.001	± 0.0005	39%	3	KTBL, 2009; Krause et al., 2016; Smaling et al., 1993	Asia, East Africa, generic, Germany, Karagwe, Kenya, TZ, Uganda
Beans, DM in biomass	% (in FM)	0.86	± 0.0	0%	2	KTBL, 2009; Krause et al., 2016	Germany, Karagwe
Beans, N in food product	% (in FM)	0.020	± 0.01	28%	8	Kimetu et al., 2008; KTBL, 2009; KTBL, 2013; Krause et al., 2016; Krug et al., 2003; Lederer et al., 2015; Smaling, et al., 1993	Germany, East Africa, Karagwe, Kenya, TZ, Uganda
Beans, N in crop residues	% (in FM)	0.011	± 0.002	21%	2	KTBL, 2009; Smaling et al., 1993	Germany, East Africa
Beans, P in food product	% (in FM)	0.003	± 0.001	25%	8	Kimetu et al., 2008; KTBL, 2009; KTBL, 2013; Krause et al., 2016; Krug et al., 2003; Lederer et al., 2015; Smaling, et al., 1993	Germany, East Africa, Karagwe, Kenya, TZ, Uganda
Beans, P in crop residues	% (in FM)	0.0008	± 0.00003	5%	2	KTBL, 2009; Smaling et al., 1993	Germany, East Africa

Onion, DM in biomass	% (in FM)	0.16	± 0.0	0%	1	Krause et al., 2016	Karagwe
Onion, N in food product	% (in FM)	0.003	± 0.002	45%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Generic, Germany, Uganda
Onion, N in crop residues	% (in FM)	0.003	± 0.002	45%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Assumed to be equivalent to N in food product
Onion, P in food product	% (in FM)	0.0005	± 0.0001	27%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Generic, Germany, Uganda
Onion, P in crop residues	% (in FM)	0.0005	± 0.0001	27%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Assumed to be equivalent to P in food product
Cabbage, DM in biomass	% (in FM)	0.64	± 0.0	0%	1	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Karagwe
Cabbage, N in food product	% (in FM)	0.003	± 0.001	43%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Generic, Germany, Uganda
Cabbage, N in crop residues	% (in FM)	0.003	± 0.001	43%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Assumed to be equivalent to N in food product
Cabbage, P in food product	% (in FM)	0.0005	± 0.0001	28%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Generic, Germany, Uganda
Cabbage, P in crop residues	% (in FM)	0.0005	± 0.0001	28%	4	KTBL, 2009; KTBL, 2013; Krug et al., 2003; Lederer et al., 2015	Assumed to be equivalent to P in food product
Moisture and nutrient concentrations in organic fertilisers							
Water in biogas slurry	g kg^{-1} (in FM)	95.6	± 0.5	1%	4	Krause et al., 2016	Karagwe
Water in standard compost	g kg^{-1} (in FM)	33.6	± 5.3	16%	4	Krause et al., 2016	Karagwe
Water in CaSa-compost	g kg^{-1} (in FM)	32.5	± 1.9	6%	4	Krause et al., 2016	Karagwe
Density biogas slurry	g (DM) dm^{-3}	44.4	± 2.2	5%	4	Krause et al., 2016	Karagwe
Density standard compost	g (DM) dm^{-3}	362.7	± 57.2	16%	4	Krause et al., 2016	Karagwe
Density CaSa-compost	g (DM) dm^{-3}	520.2	± 31.0	6%	4	Krause et al., 2016	Karagwe
Density biogas slurry	g (FM) dm^{-3}	1000.0	± 50.0	5%	4	Krause et al., 2016	Karagwe
Density standard compost	g (FM) dm^{-3}	546.5	± 1.5	0%	4	Krause et al., 2016	Karagwe
Density CaSa-compost	g (FM) dm^{-3}	770.5	± 8.9	1%	4	Krause et al., 2016	Karagwe
Total C in biogas slurry	g kg^{-1} (in DM)	347.8	± 6.4	2%	4	Krause et al., 2016	Karagwe
Total C in standard compost	g kg^{-1} (in DM)	90.60	± 7.7	8%	4	Krause et al., 2016	Karagwe
Total C in CaSa-compost	g kg^{-1} (in DM)	115.6	± 11.4	10%	4	Krause et al., 2016	Karagwe
Total C in biogas slurry	g kg^{-1} (in FM)	15.3	± 0.3	2%	4	Krause et al., 2016	Karagwe
Total C in standard compost	g kg^{-1} (in FM)	60.16	± 10.8	18%	4	Krause et al., 2016	Karagwe
Total C in CaSa-compost	g kg^{-1} (in FM)	78.03	± 8.9	11%	4	Krause et al., 2016	Karagwe
Total N in biogas slurry	g kg^{-1} (in DM)	19.8	± 0.1	1%	4	Krause et al., 2016	Karagwe
Total N in standard compost	g kg^{-1} (in DM)	5.3	± 0.2	4%	4	Krause et al., 2016	Karagwe
Total N in CaSa-compost	g kg^{-1} (in DM)	6.0	± 0.5	8%	4	Krause et al., 2016	Karagwe
Total N in biogas slurry	g kg^{-1} (in FM)	0.9	± 0.0	1%	4	Krause et al., 2016	Karagwe
Total N in standard compost	g kg^{-1} (in FM)	3.5	± 0.6	16%	4	Krause et al., 2016	Karagwe
Total N in CaSa-compost	g kg^{-1} (in FM)	4.0	± 0.4	10%	4	Krause et al., 2016	Karagwe
Total P in biogas slurry	g kg^{-1} (in DM)	7.6	± 0.2	3%	4	Krause et al., 2016	Karagwe
Total P in standard compost	g kg^{-1} (in DM)	1.2	± 0.1	8%	4	Krause et al., 2016	Karagwe
Total P in CaSa-compost	g kg^{-1} (in DM)	3.2	± 0.2	6%	4	Krause et al., 2016	Karagwe
Total P in biogas slurry	g kg^{-1} (in FM)	0.3	± 0.0	3%	4	Krause et al., 2016	Karagwe
Total P in standard compost	g kg^{-1} (in FM)	0.8	± 0.1	18%	4	Krause et al., 2016	Karagwe
Total P in CaSa-compost	g kg^{-1} (in FM)	2.1	± 0.2	9%	4	Krause et al., 2016	Karagwe
Fate of harvest residues							
DM content residues	% FM	0.691	± 0.069	10%	9	Krause et al., 2016	Karagwe

Ash content residues	% DM	0.120	± 0.024	20%	-	Assumption	
Burned	% (of FM)	0.02	± 0.01	48%	4	Mavuno, 2015	Karagwe
Composting	% (of FM)	0.41	± 0.07	16%	4	Mavuno, 2015	Karagwe
Mulching	% (of FM)	0.47	± 0.07	14%	4	Mavuno, 2015	Karagwe
Others	% (of FM)	0.10	± 0.03	27%	4	Mavuno, 2015	Karagwe
Emissions from burning agricultural residues							
CO_2	g kg^{-1} DM burnt	1515	± 177	12%		Aalde et al., 2006	Table 2.5, 'agricultural residues'
CO	g kg^{-1} DM burnt	92	± 84	91%		Aalde et al., 2006	Table 2.5, 'agricultural residues'
CH_4	g kg^{-1} DM burnt	2.7	± 0.8	*30%*		Aalde et al., 2006	Table 2.5, 'agricultural residues'
N_2O	g kg^{-1} DM burnt	0.1	± 0.02	*30%*		Aalde et al., 2006	Table 2.5, 'agricultural residues'
Nox	g kg^{-1} DM burnt	2.5	± 1.0	40%		Aalde et al., 2006	Table 2.5, 'agricultural residues'
Mulching and grass carpeting							
Grass applied for carpeting	kg (FM) ha^{-1} yr^{-1}	1500	± 450	30%	1	Krause et al., 2016	Karagwe
Total N in grass	% N (in FM)	0.004	± 0.0002	4%	2	Calculation, based on Baijukya et al., 1998	Kagera, Karagwe
Total P in grass	% P (in FM)	0.001	± 0.0002	25%	2	Calculation, based on Baijukya et al., 1998	Kagera, Karagwe
N-recycling of carpeting/mulching	% N	0.87	± 0.03	3%	5	Calculation, based on Larsson et al., 1998; Möller and Stinner, 2009; Schmidt, 1997	Germany, Sweden
P-recycling of carpeting/mulching	% P	1	0			Assumption	Karagwe
Gaseous N losses through denitrification (N_2O)	% N	0.016	± 0.003	18%	3	Calculation, based on Larsson et al., 1998; Möller and Stinner, 2009	Germany, Sweden
Gaseous N losses through volatization (NH_3)	% N	0.115	± 0.03	26%	2	Calculation, based on Larsson et al., 1998; Schmidt, 1997	Germany, Sweden
Composting: characteristics of the used materials							
Kitchen waste	kg p^{-1} d^{-1}	0.08	± 0.02	30%		Meinzinger, 2010	Ethiopia
Kitchen waste to compost	% FM	0.8	± 0.08	10%		Lederer et al., 2015	directly to cropland or in compost; Uganda
Total C in kitchen waste	% FM	0.239	± 0.11	44%		Calculation, based on Meinzinger, 2010	Ethiopia
Total N in kitchen waste	% FM	0.0045	± 0.002	37%		Calculation, based on Meinzinger, 2010	Ethiopia
Total P in kitchen waste	% FM	0.0010	± 0.0004	36%		Calculation, based on Meinzinger, 2010	Ethiopia
Total C in local soil (Andosol)	% FM	0.029	± 0.001	2%	5	Krause et al., 2016	Karagwe
Total N in local soil (Andosol)	% FM	0.002	± 0.00005	2%	5	Krause et al., 2016	Karagwe
Total P in local soil (Andosol)	% FM	0.0011	± 0.0003	25%	1	Towett et al., 2015	TZ: Kisongo
Composting: process parameters							
Compost per input	kg kg^{-1} (FM)	0.6050	± 0.07	11%	2	Calculation, based on Belevi, 2002; Uenosono et al., 2002	Considering rotting losses ; generic, Japan
N transfer to compost	% N	0.697	± 0.10	14%	3	Calculation, based on Amlinger et al., 2005; Belevi, 2002; Leitzinger, 1999; Sonesson et al., 1997	Generic, Ghana, NA
N transfer into gaseous emissions	% N	0.343	± 0.08	23%	2	Calculation, based on Beck-Friis et al., 2000; Belevi, 2002;	Generic, Sweden
NH_3 in gaseous N-emissions	% gas. N loss	0.950	± 0.29	30%	1	Beck-Friis,et al., 2000	Sweden
N_2O in gaseous N-emissions	% gas. N loss	0.050	± 0.02	30%	1	Beck-Friis et al., 2000	Sweden
P transfer to compost	% P	0.950	± 0.10	10%	3	Assumption, based on Belevi, 2002; Leitzinger, 1999	Generic, Ghana
P transfer to leachate	% P	0.050	± 0.01	10%	3	Assumption, based on Belevi, 2002; Leitzinger, 1999	Generic; average is 0.01 ± 0.01; we assumed increased leaching, because of heavy rain falls in rainy season and un-roofed compost places
C transfer to compost	% C	0.525	± 0.10	20%	2	Calculation, based on Leitzinger, 1999; Uenosono et al., 2002	Ghana, Japan
C transfer gaseous emissions (CO_2)	% C	0.480	± 0.07	14%	2	Calculation, based on Beck-Friis, et al., 2000; Morand et al., 2005	Sweden

Urine as mineral fertilizer							
N in stored urine from UDDT	g dm^{-3}	5.0	± 1.19	24%	9	Calculation, based on FAO, n.d; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Krause and Rotter, 2017; Meinzinger, 2010; Montangero, 2006	Europe, Ethiopia, Tanzania, Uganda, Vietnam
P in stored urine from UDDT	g dm^{-3}	0.5	± 0.23	47%	9	Calculation, based on FAO, n.d; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Jönsson and Vinnerås, 2004; Krause and Rotter, 2017; Meinzinger, 2010; Montangero, 2006	Europe, Ethiopia, Tanzania, Uganda, Vietnam
N-recycling of urine	% N	0.877	± 0.02	3%		Calculation, from NH_3 emissions, N_2O emissions, and N-leaching	
Emissions from fertilizer application							
NH_3 emissions, urine application	% N	0.073	± 0.017	24%	3	Calculation, based on Jönsson, 2002; Prasertsak et al., 2001; Rodhe et al., 2004	N losses through volatilization; urine assumed as mineral fertilizations; Australia, generic, Sweden
NH_3 emissions, mulching	% N	0.115	± 0.030	26%	2	Calculation, based on Larsson et al., 1998; Schmidt, 1997	N losses through volatilization; Germany, Sweden
NH_3 emissions, compost amendment	% N	0.000	± 0.000			Assumption, based on Möller and Stinner, 2009	Neglected because according to literature, NH_3-emissions depend on NH_4-content, which is hardly found in solid compost; Germany
NH_3 emissions, biogas slurry amendment	% N	0.139	± 0.022	16%	4	Calculation, based on Amon et al., 2006; Möller and Stinner, 2009	N losses through volatilization; Germany
N_2O emissions, mulching	% N	0.016	± 0.003	18%	3	Calculation, based on Larsson et al., 1998; Möller and Stinner, 2009	Germany, Sweden
N_2O emissions, application of urine and biogas slurry	% N	0.009	± 0.002	21%	3	Calculation, based on Amon et al., 2006; Möller and Stinner, 2009	Germany
Nitrate leaching	% N	0.041	± 0.015	37%	2	Calculation, based on Prasertsak et al., 2001	Liquid N-losses; Australia
Densities of selected materials in FM							
Ashes	kg dm^{-3}	0.39	± 0.12	31%		Chaggu, 2004	Tanzania
Biochar	kg dm^{-3}	0.27	± 0.10	37%		Lehmann and Joseph, 2009	Generic
Grasses (weeds)	kg dm^{-3}	0.08	± 0.00	1%		Krause et al., 2016	Karagwe
Harvest residues	kg dm^{-3}	0.30	± 0.06	20%		Assumption, based on Krause et al., 2016	Karagwe
Mix of grasses, weeds, harvest residues	kg dm^{-3}	0.24	± 0.03	12%		Calculation, based on Krause et al., 2016	Karagwe
Organic waste	kg dm^{-3}	0.61	± 0.30	49%		Meinzinger, 2010	Generic
Mineral mix	kg dm^{-3}	0.58	± 0.08	14%		Calculation, based on Chaggu, 2004; Krause et al., 2016; Venkataraman et al., 2004	Karagwe, India, Tanzania
Sanitized faeces and dry material	kg dm^{-3}	0.51	± 0.08	17%		Calculation, based on own experiments, March 2015	Karagwe
Sawdust	kg dm^{-3}	0.26	± 0.10	38%		Venkataraman et al., 2004	India
Soil	kg dm^{-3}	1.00	± 0.10	10%		Krause et al., 2016	Karagwe
Urine	kg dm^{-3}	1.00	± 0.05	5%		Assumption, based on UPB, n.d.	Germany
Biogas slurry	kg dm^{-3}	1.0	± 0.05	5%		Krause et al., 2015; based on Vögeli et al., 2014	Karagwe
Standard compost	kg dm^{-3}	0.55	± 0.002	0%		Krause et al., 2015	Karagwe
CaSa-compost	kg dm^{-3}	0.77	± 0.009	1%		Krause et al., 2015	Karagwe

Non-common abbreviations: BNF: biological nitrogen fixation; CaSa: 'Carbonization and Sanitation'; DM: dry matter; Eq.: equation; FM: fresh matter; NA: not available; NB: natural balance; p^{-1}: per person; PB: partial balance; RU: relative uncertainty; UDDT: urine diverting dry toilet; $\bar{x}$: mean value; Δx: standard error

Table S33: List of plausibility criteria used for evaluation of estimated results from system.

Sub-system	Criteria	Source
AES	SNB	Baijukya, 1998; Lederer et al., 2015; Stoorvogel et al., 1993
AES	BNF	Baijukya, 1998; Lesschen et al., 2007; Nkonya et al., 2005; Stoorvogel et al., 1993; Wortmann and Kaizzi, 1998
AES	Application rates of compost	Buresh, 2007; Finck, 2007; Mafongoya et al., 2007
AES	Application rates of urine	Richert et al., 2010

Non-common abbreviations: AES: agroecosystem; BNF: biological nitrogen fixation; SNB: soil nutrient balancing

Supplementary 6. TERMINOLOGY

In our work, which refers specifically to smallholder farming in Karagwe, TZ, we use some specific words which we briefly introduce in the following paragraph:

Msiri	Swahili for former grassland used for cultivation of annual crops like maize, beans as well as vegetables, which is also a kitchen garden.
Shamba	Swahili for banana-based home gardens that are intercropped with other fruit trees, beans, coffee, egg-plant, etc.
Biogas slurry	Residue that derives from anaerobic digestion of banana tree stumps and cow dung (mixture 2:1 by volume).
CaSa-compost	Product of CaSa-concept to sanitation, which contains pasteurised human faeces, kitchen waste, harvest residues, terracotta particles, ashes, and urine mixed with biochar recovered as residues from microgasifier stoves used for cooking or thermal sanitation.
Standard compost	Compost as commonly prepared by farmers in Karagwe, which contains a mixture of fresh and dried grasses, ash, and kitchen waste.
Solids	Matter collected inside a urine diverting dry toilet (UDDT), which comprise faeces, dry material, some urine which enters the into the compartment for solids' collection due to incomplete urine diversion, and toilet paper.
Urine	Liquid part of human excreta collected in UDDT.
Harvest product	Total above-ground biomass of crops.
Food product	Weight of marketable product of crops, including maize grains, bean seeds, onion bulbs, and cabbage heads after a week's drying in the sun (except for cabbage, which is fresh weight at time of harvesting).

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List of Abbreviations

AirIn	Input of air
AirOut	Output of air
Ash & char	Residues available after cooking with a microgasifier, i.e. a mix of ash and char particles
A	Ash
AES	Agroecosystem
AM	Abbreviation agroecosystem of a msiri
BiogaST	Project 'Biogas Support for Tanzania'
BNF	Biological nitrogen fixation
C	Carbon
c	Concentration
CaSa	Project 'Carbonization and Sanitation'
CHEMA	Programme for Community Habitat Environmental Management, a local NGO and project partner of the present research project
DM	Dry matter
E	Export flow
EF	Emission factor
EfCoiTa	Project 'Efficient Cooking in Tanzania'
EP	Eutrophication potential
FM	Fresh matter
FP	Food Product
G	Good
GHG	Greenhouse gas
GWP	Global warming potential
HH	Households
HR	Harvest residue
I	Import flow
IN	Input flows
IPCC	Intergovernmental Panel on Climate Change
IPNM	Integrated plant nutrient management
KW	Kitchen waste
LU	Land use
$\dot{m}$	Annual material flows
MAVUNO	Swahili for 'harvest', name of a local NGO and project partner of the present research project
MES	Micro energy system
MF	Model factor
MFA	Material flow analysis
MSS	Micro sanitation system
n	Total sample size, i.e. number of replications
N	Nitrogen
NA	Not analysed
NB	Natural balance
NGO	Non-governmental organisation
OUT	Output flows
P	Phosphorus
PB	Partial balance
σ	Standard deviation
SNB	Soil nutrient balances
STAN	SubSTance flow Analysis (software)
TC	Transfer coefficients
TZ	Tanzania
UDDT	Urine diverting dry toilet

Words in Swahili:

Shamba	Fields used for intercropping of perennial and annual crops, located directly surrounding smallholders houses and also referred to as 'banana-based home gardens'.
Msiri	Fields used for intercropping system of annual crops; surrounding *shamba*.

S4: Supplement of P5

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SUPPLEMENTARY MATERIAL OF

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

A. Krause, J. Köppel
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

TABLE OF CONTENTS

PRELIMINARY REMARK

The present document supplements a manuscript about a method developed called the 'multi-criteria technology assessment' (MCTA). This supplements contains graphical visualizations, additional to those presented in the main article and plot data to graphical visualizing results presented in the main article as well as in the present supplements. In addition, results of the final evaluation with participants of the MCTA are presented.

FIGURES

Results of the self-assessment of participants

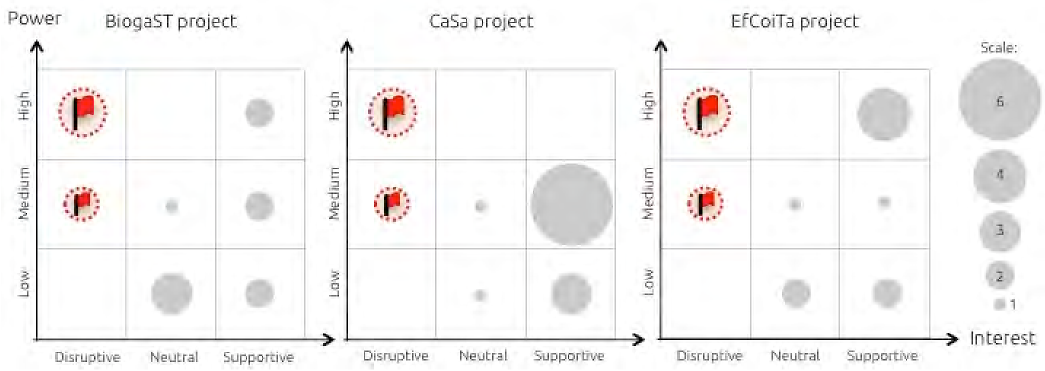

Fig. S.1: Rating of the participants concerning their individual power and interest in the three case studies of this work

Among all participants of the MCTA, there was no person who had high power to decide about the future course of the project but showed disruptive interest in the project. In practice, there would be the risk that this person could be a "potential project breaker" according to Lohri (2009). This means, that the respective stakeholder has the power for example to prevent the implementation of the technologies just because of his or her own opinion rather then the will of the community. In the described situation, a high potential for conflicts exists (indicated by the red flag). Hence, the assessment should be interfered to address and clear the specific conflict. Before continuing the assessment, the situation shall be improved in collaboration with the stakeholders. For example, an open discussion my clear the conflict or an exchange of the respective stakeholder would be required. However, here we had no such situation and thus continued with the MCTA.

Results of the weighting process

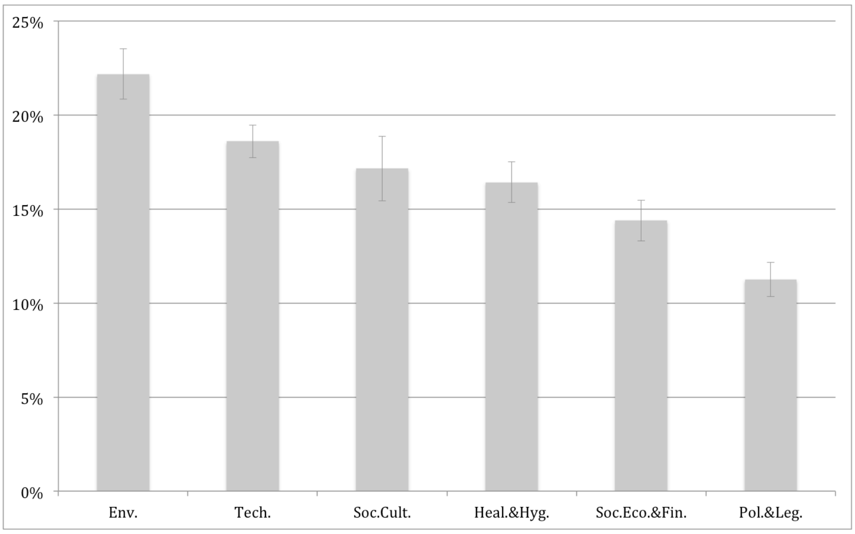

Fig. S.2: The relative importance of the six main-criteria represented by the relative weight of each main-criterion (in %) as an average of the weights from all participants and ranked from the most important (left) to the least important (right). Error bars indicate the standard error of the mean (SEM).

Results of sustainability index for cooking and sanitation alternatives

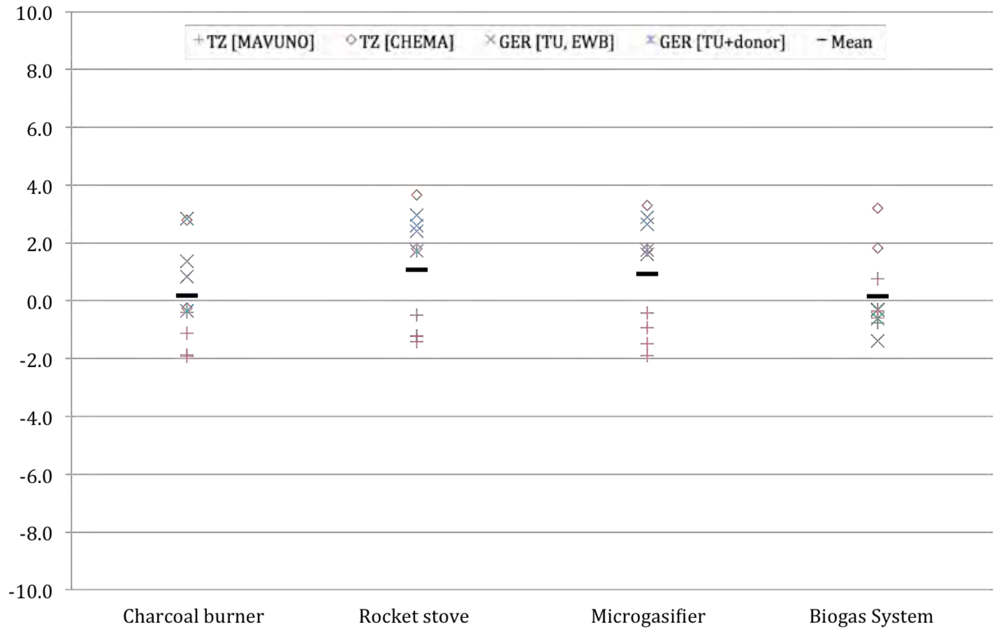

Fig. S.3: Color-coded scatter plot of the overall sustainability index (SI) of cooking alternatives analysed of Tanzanian (red) and German participants (blue) alongside the average of all participants (grey). [The index ranges from -10 to +10 with an alternative being strongly unfavourable (-10), unfavourable (-5), acceptable (0), favourable (+5), or very favourable (+10).]

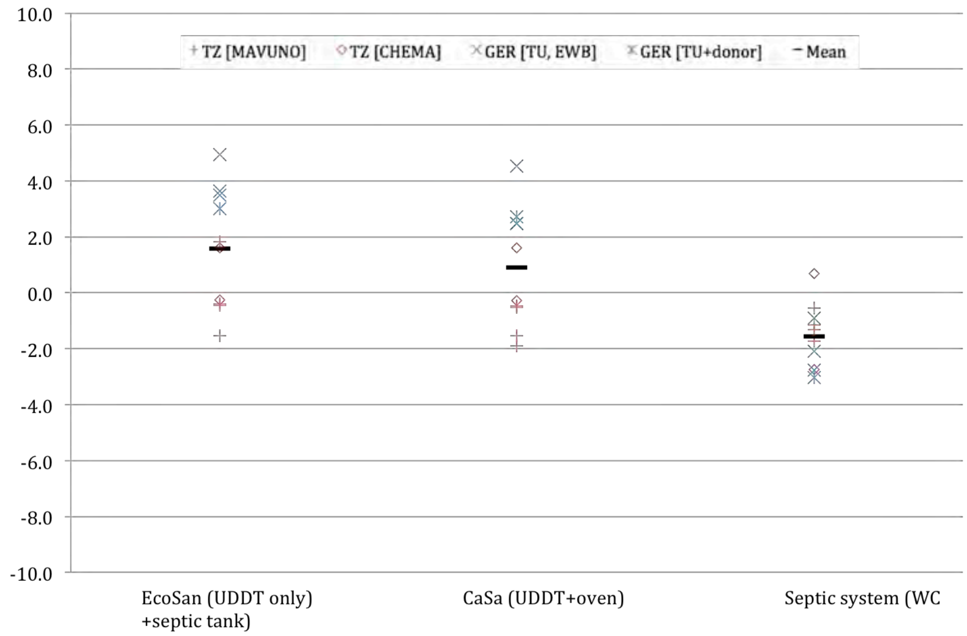

Fig. S.4: Color-coded scatter plot of the overall sustainability index (SI) of sanitation alternatives analysed of Tanzanian (red) and German participants (blue) alongside the average of all participants (grey). [The index ranges from -10 to +10 with an alternative being strongly unfavourable (-10), unfavourable (-5), acceptable (0), favourable (+5), or very favourable (+10).]

Results of the assessment of the energy technologies

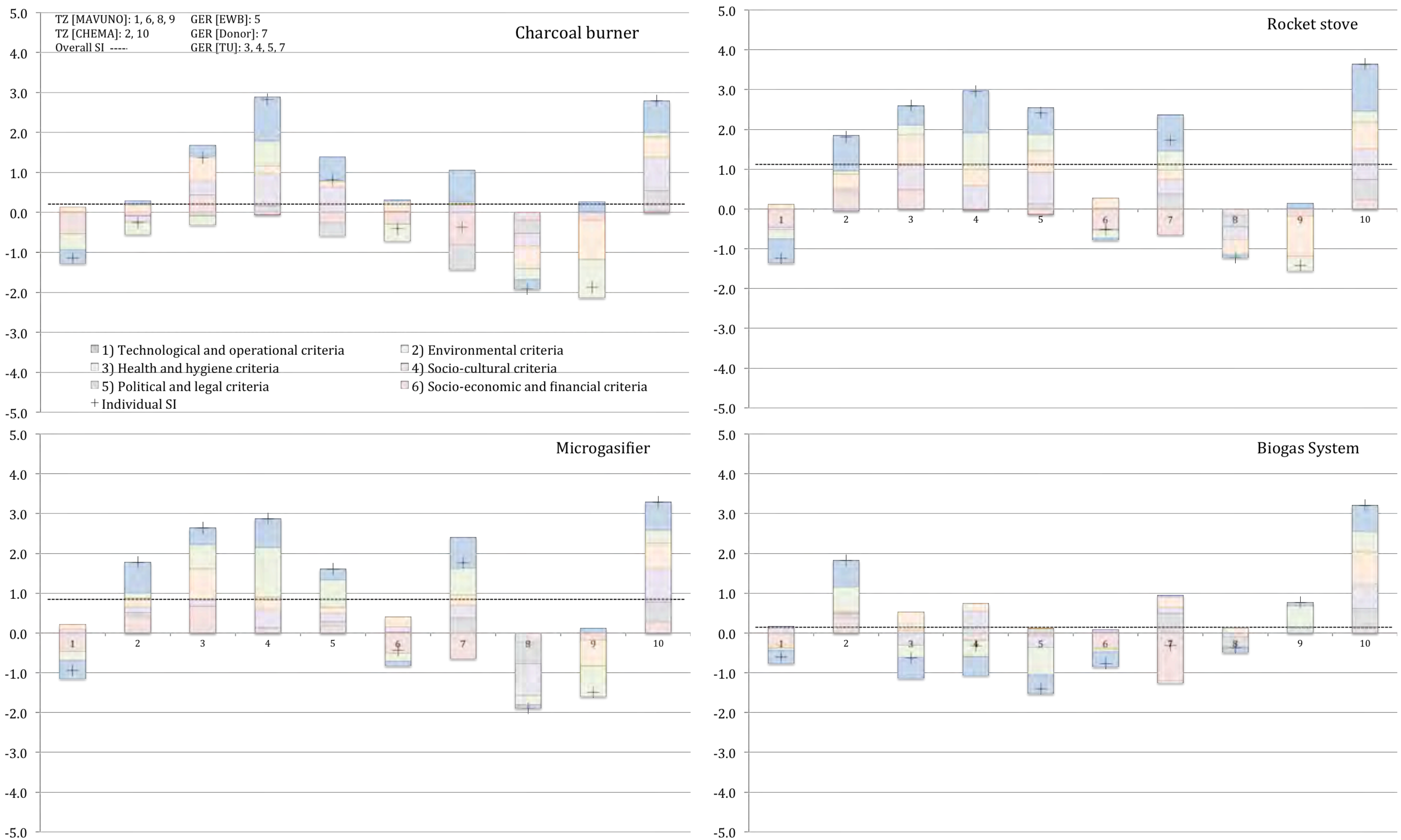

Fig. S.5: Distribution of the individual SIs (+) as balance of positive and negative weighted scores of the different main-criteria (colours explained in legend) for all participants (1 to 10; legend indicates affiliation of participants) and alongside the mean SI of all participants. (black dotted line).

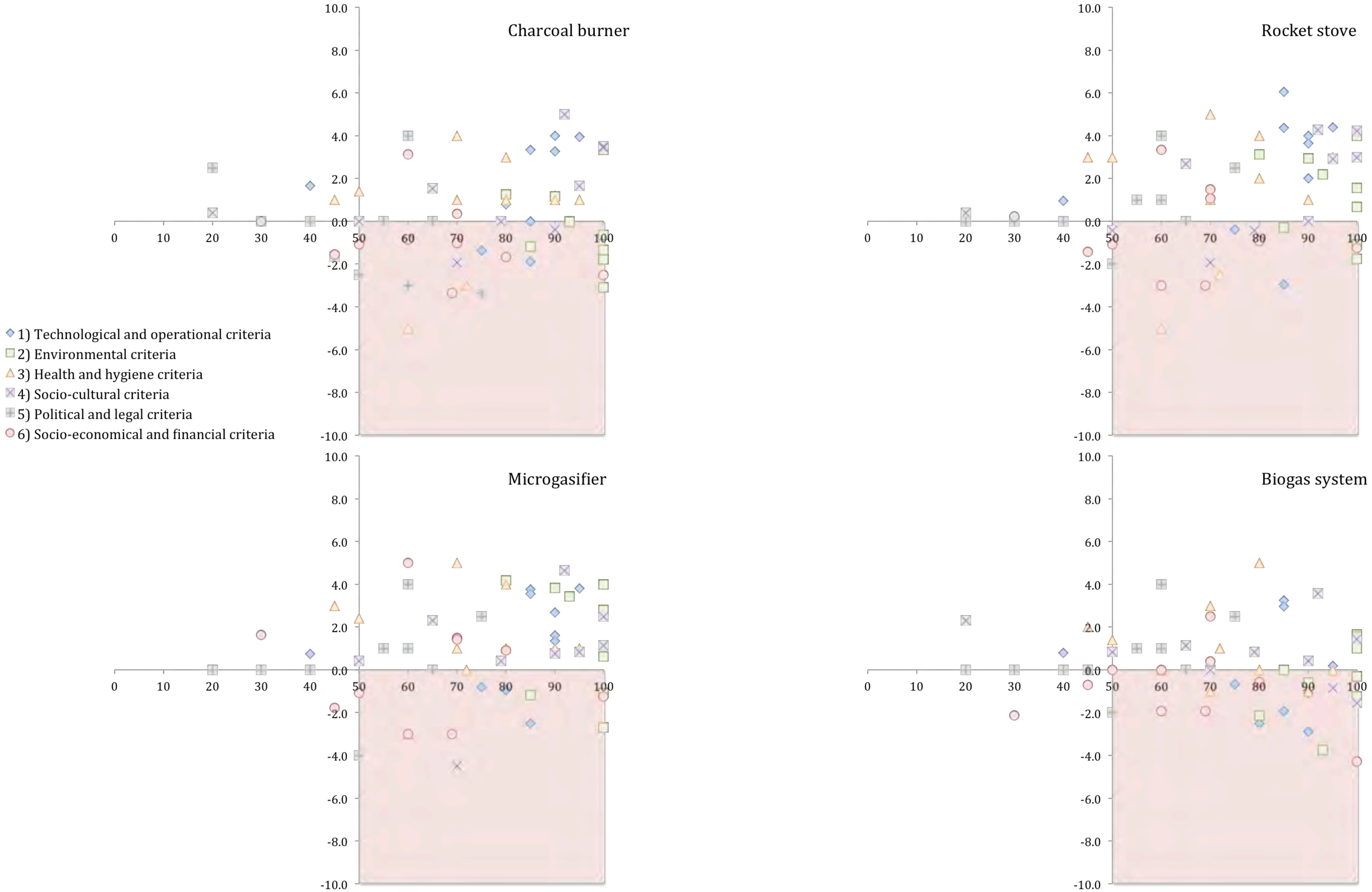

Fig. S.6: Results of the scoring (y-axis) and weighting (x-axis) of cooking alternatives. The graphs present results for all main-criteria (color-coded symbols) and for all participants (number of signs). The 'red area' indicates that a criterion was given above-average importance but the performance was not perceived as favourable.

Results of the assessment of the sanitation technologies

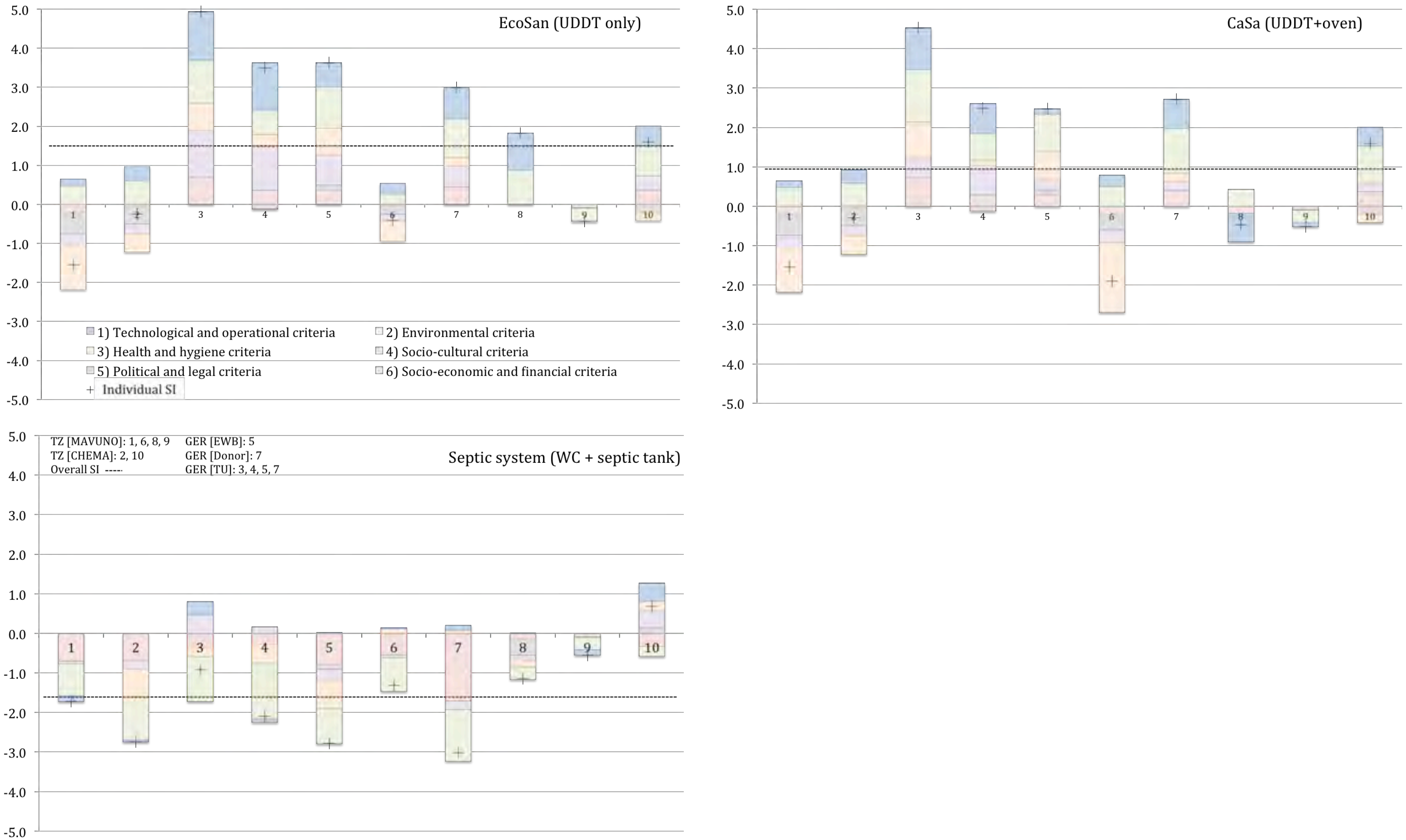

Fig. S.7: Distribution of the individual SIs (+) as balance of positive and negative weighted scores of the different main-criteria (colours explained in legend) for all participants (1 to 10; legend indicates affiliation of participants) and alongside the mean SI of all participants. (black dotted line).

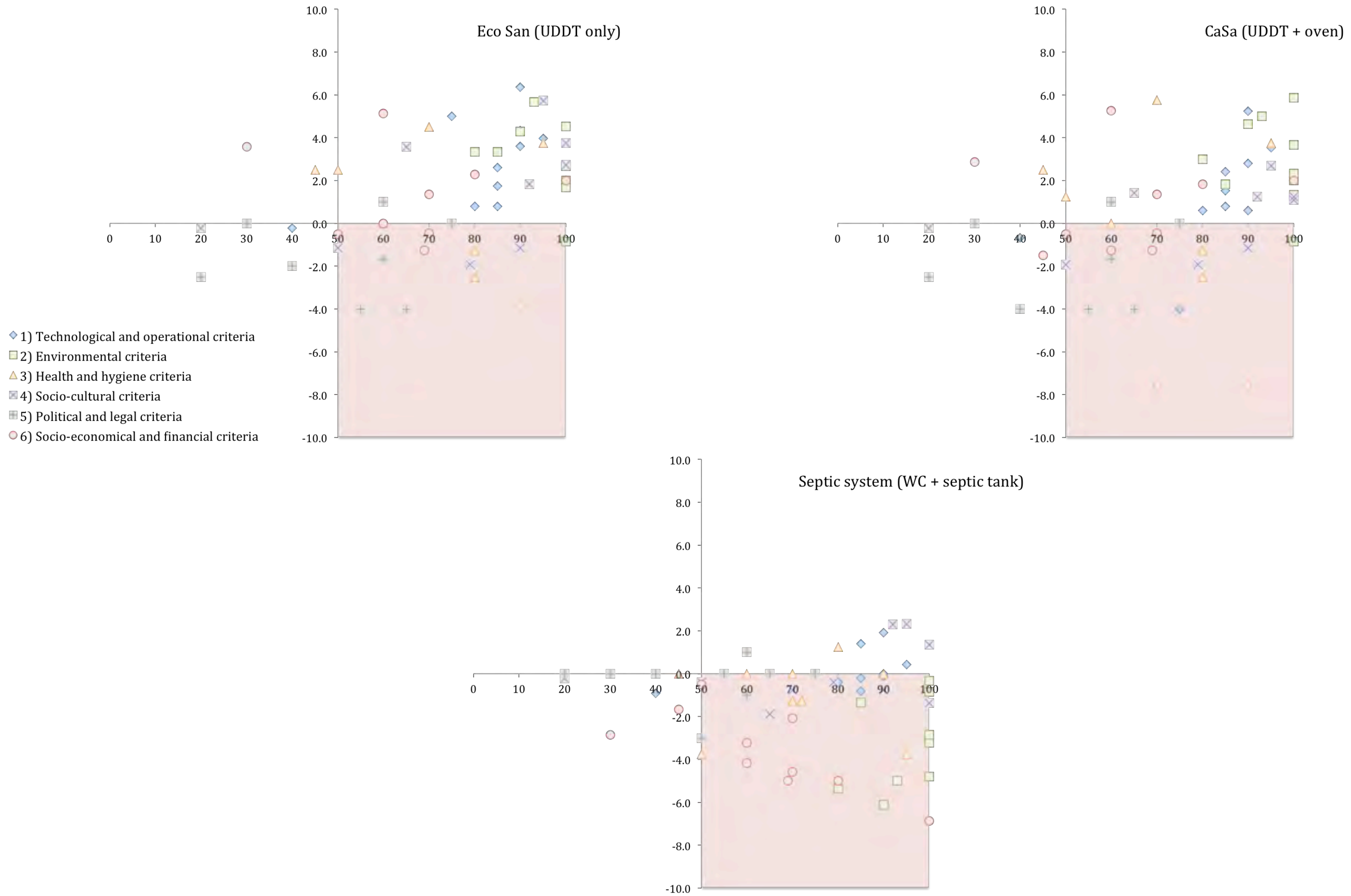

Fig. S.8: Results of the scoring (y-axis) and weighting (x-axis) of sanitation alternatives. The graphs present results for all main-criteria (color-coded symbols) and for all participants (number of signs). The ‘red area’ indicates that a criterion was given above-average importance but the performance was not perceived as favourable.

Short discussion of Figs S.5-S.8

Figure S.6 reveals that for charcoal burner, rocket stove, microgasifier, and biogas system, respectively, 18, 13, 11, and 19 judgements out of a total of 60 are found in the 'red area'. Hence, for microgasifier and rocket stoves, most main-criteria considered important are assessed positively; only one sixth of judgements are in the 'red area'. However, for charcoal and biogas alternatives about one third of the important main-criteria are in the 'red area'. Improvements to rocket stoves and microgasifiers primarily pertain to socio-economic/financial criteria whilst charcoal and biogas alternatives need major general improvements because all main-criteria are represented within 'red area'.

Looking at sanitation alternatives (Fig. S.8), we find that for EcoSan, CaSa, and septic system, respectively, 11, 11, and 29 judgements out of a total of 60 are found in the 'red area'. Hence, for the EcoSan- and CaSa-alternatives, most main-criteria considered important are assessed positively. Only one sixth of judgements are in the 'red area' indicating that both ecological alternatives need improvement with respect to health/hygiene and political/legal criteria. For the septic system however, about half of the important criteria receive negative scorings. This signifies that it seems difficult to meet SCD aims while implementing septic systems, even with strong improvements.

Results of the evaluation of the final feedback

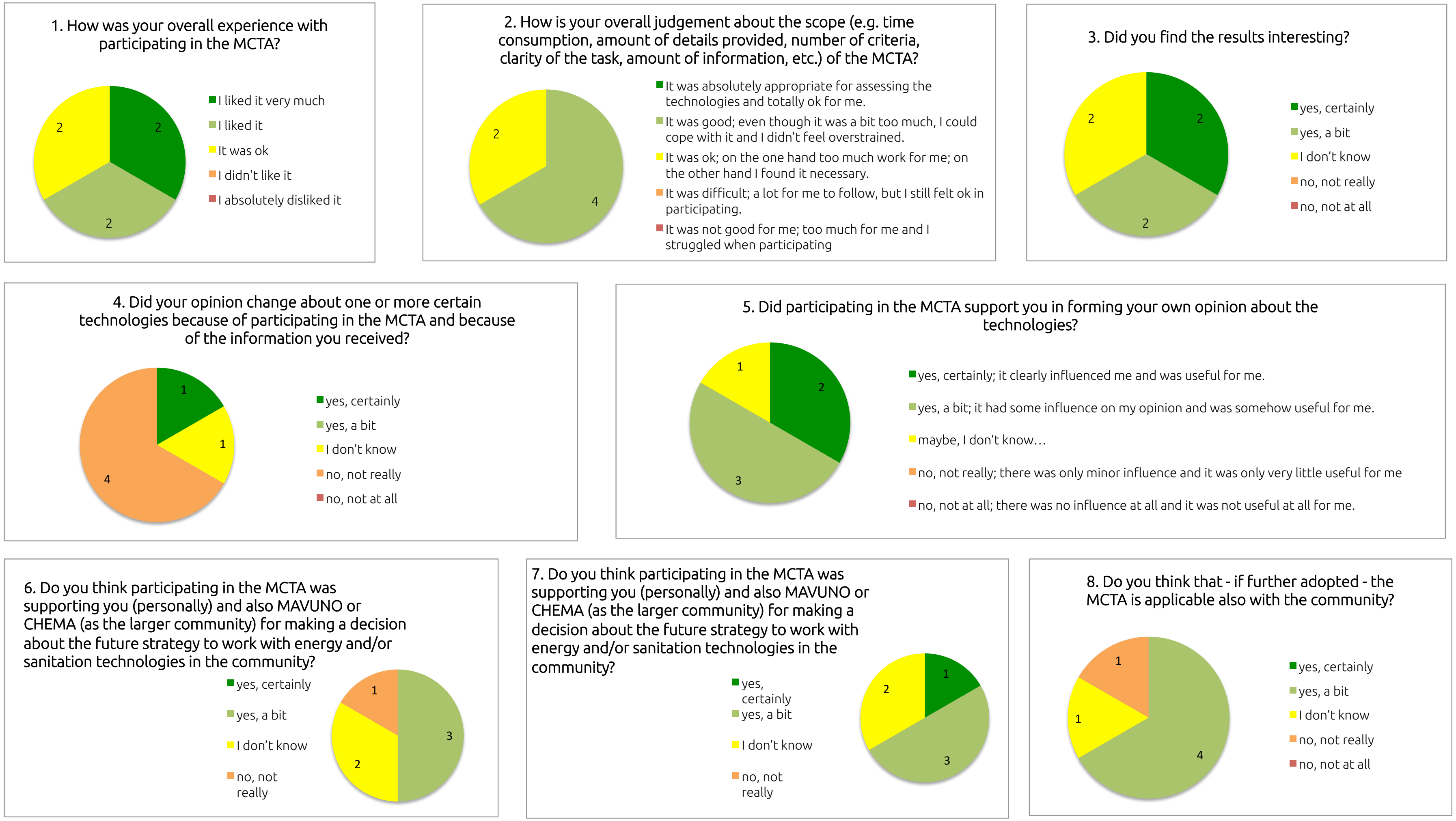

Fig. S.9: Results from evaluating the feedback questionnaires given to participants at the end of the MCTA. Evaluation includes answers received from 6 out of 10 participants.

TABLES

Table S.1: Results of weighting the main-criteria: ‘individual relative weights’ for ten participants; plot data for Fig. 3.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria
1	0.18	0.21	0.15	0.17	0.14	0.15
2	0.18	0.21	0.17	0.19	0.11	0.15
3	0.20	0.22	0.15	0.21	0.10	0.13
4	0.24	0.22	0.14	0.27	0.05	0.08
5	0.17	0.18	0.18	0.19	0.12	0.15
6	0.19	0.24	0.21	0.12	0.10	0.14
7	0.20	0.19	0.10	0.14	0.16	0.21
8	0.19	0.21	0.18	0.18	0.13	0.11
9	0.13	0.33	0.20	0.07	0.10	0.17
10	0.17	0.21	0.16	0.19	0.12	0.14
Mean	0.19	0.22	0.16	0.17	0.11	0.14

Table S.2: Results of weighting the main-criteria: ‘relative weight’ as average of all participants; plot data for Fig. S.2.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria
Mean	0.19	0.22	0.16	0.17	0.11	0.14
SEM	0.01	0.01	0.01	0.02	0.01	0.01
Max	0.24	0.33	0.21	0.27	0.16	0.21
Min	0.13	0.18	0.10	0.07	0.05	0.08
$\Delta_{min.}^{max.} \approx$	0.11	0.15	0.12	0.20	0.11	0.13

Non-common abbreviations: SEM: Standard error of the mean

Table S.3: Results of assessment: ‘overall SI’ of cooking alternatives analysed as mean value of all participants; plot data for Fig. 4.

	Charcoal burner	Rocket stove	Microgasifier	Biogas system
Mean	0.2	1.1	0.9	0.1
SEM	0.5	0.6	0.6	0.4

Non-common abbreviations: SEM: Standard error of the mean; SI: Sustainability index

Table S.4: Results of assessment: ‘overall SI’ of sanitation alternatives analysed as mean value of all participants; plot data for Fig. 6.

	EcoSan (UDDT only)	CaSa (UDDT + oven)	Septic system (WC + septic tank)
Mean	1.6	0.9	-1.6
SEM	0.7	0.7	0.4

Non-common abbreviations: CaSa: Carbonization and Sanitation; EcoSan: Ecological sanitation; SEM: Standard error of the mean; SI: Sustainability index; UDDT: Urine-diverting dry toilet; WC: water closet

Table S.5: Results of assessment: ‘individual SI’ of cooking alternatives analysed for ten participants; plot data for Fig. S.3.

	Charcoal burner	Rocket stove	Microgasifier	Biogas system
1	-1.1	-1.2	-0.9	-0.6
2	-0.2	1.8	1.8	1.8
3	1.4	2.6	2.6	-0.6
4	2.8	3.0	2.9	-0.3
5	0.8	2.4	1.6	-1.4
6	-0.4	-0.5	-0.4	-0.8
7	-0.4	1.7	1.8	-0.3
8	-1.9	-1.2	-1.9	-0.4
9	-1.9	-1.4	-1.5	0.8
10	2.8	3.6	3.3	3.2
Mean	0.2	1.1	0.9	0.1

Non-common abbreviations: SI: Sustainability index

Table S.6: Results of assessment: 'individual SI' of sanitation alternatives analysed for ten participants; plot data for Fig. S.4.

	EcoSan (UDDT only)	CaSa (UDDT + oven)	Septic system (WC + septic tank)
1	-1.5	-1.5	-1.7
2	-0.2	-0.3	-2.7
3	4.9	4.5	-0.9
4	3.5	2.5	-2.1
5	3.6	2.5	-2.8
6	-0.4	-1.9	-1.3
7	3.0	2.7	-3.0
8	1.8	-0.5	-1.1
9	-0.4	-0.5	-0.6
10	1.6	1.6	0.7
Mean	1.6	0.9	-1.6

Non-common abbreviations: CaSa: Carbonization and Sanitation; EcoSan: Ecological sanitation; SEM: Standard error of the mean; SI: Sustainability index; UDDT: Urine-diverting dry toilet; WC: water closet

Table S.7: Results of scoring: 'Individual weighted scores' of cooking alternatives for ten participants, scores assigned for sub-criteria are weighted with relative weights of sub-criteria and aggregated to the level of main criteria (Eq. A.7) for main-criteria; plot data for Fig. 5.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria	SI
Charcoal burner							
1	-1.9	-1.9	0.8	0.1	0.0	-3.5	-1.1
2	0.5	-1.6	1.3	-0.8	0.0	-0.5	-0.2
3	1.4	-1.0	4.0	1.7	-0.8	3.4	1.4
4	4.5	2.9	1.4	3.0	2.9	-0.7	2.8
5	3.4	0.1	0.8	3.3	-2.8	-1.6	0.8
6	0.2	-1.8	1.2	0.1	0.2	-2.0	-0.4
7	3.9	0.2	0.4	1.3	-4.0	-3.7	-0.4
8	-1.3	-1.3	-3.1	-1.9	-2.6	-1.6	-1.9
9	1.8	-2.9	-5.0	0.4	0.0	-1.0	-1.9
10	4.5	0.5	3.1	4.5	4.1	0.3	2.8
Mean	1.7	-0.7	0.5	1.2	-0.3	-1.1	0.2
Rocket stove							
1	-3.4	-1.1	0.8	-0.4	0.0	-3.0	-1.2
2	5.1	0.4	2.2	-0.2	0.9	2.8	1.8
3	2.4	1.2	5.0	3.1	0.0	3.7	2.6
4	4.4	4.3	3.0	2.2	0.0	-0.3	3.0
5	3.8	2.4	2.9	4.2	1.0	-0.9	2.4
6	-0.3	-0.9	1.2	-0.2	0.2	-3.5	-0.5
7	4.5	2.4	2.6	2.7	2.3	-3.0	1.7
8	-0.3	-0.2	-2.0	-1.8	-2.2	-1.4	-1.2
9	0.9	-1.1	-5.0	0.4	0.0	-1.0	-1.4
10	6.8	1.4	4.0	4.1	4.1	1.7	3.1
Mean	2.4	0.9	1.5	1.4	0.6	-0.5	1.1
Microgasifier							
1	-2.6	-1.1	0.8	0.6	0.0	-3.0	-0.9
2	4.3	0.6	1.3	0.8	0.9	2.8	1.8
3	2.1	2.8	5.0	0.9	0.0	5.2	2.6
4	3.0	5.7	2.4	1.7	0.0	1.5	2.9
5	1.6	3.8	0.8	1.1	1.0	1.1	1.6
6	-0.6	-0.9	1.2	1.1	0.2	-3.5	-0.4
7	3.8	3.5	2.6	2.5	2.3	-3.0	1.8
8	-0.5	-1.1	0.0	-4.6	-4.4	-1.8	-1.9
9	0.9	-2.3	-3.2	0.0	0.0	-1.0	-1.5
10	4.1	1.5	4.0	4.4	4.1	1.9	2.8
Mean	1.6	1.3	1.5	0.8	0.4	0.0	0.9
Biogas system							
1	-1.9	-0.3	-0.5	1.0	0.0	-1.9	-0.6
2	3.7	3.1	0.1	0.2	0.9	2.6	1.8
3	-2.7	-1.4	3.0	-1.4	0.0	0.5	-0.6
4	-2.0	-1.8	1.4	2.0	0.0	-2.3	-0.3
5	-2.8	-3.8	0.1	-1.5	0.9	-0.4	-1.4
6	-2.0	-0.3	-0.2	0.5	0.2	-2.4	-0.8
7	0.2	-0.3	2.9	1.1	3.1	-5.6	-0.3
8	-0.7	0.0	0.7	-0.1	-2.0	-0.8	-0.4
9	0.7	1.6	0.0	2.2	0.0	0.0	0.8
10	3.7	2.5	4.9	3.3	4.1	0.8	3.2
Mean	-0.4	-0.1	1.2	0.7	0.7	-0.9	0.1

Non-common abbreviations: SI: Sustainability index

Table S.8: Results of scoring: 'Individual weighted scores' of sanitation alternatives for ten participants, scores assigned for sub-criteria are weighted with relative weights of sub-criteria and aggregated to the level of main criteria (Eq. A.7) for main-criteria; plot data for Fig. 7.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria	SI
EcoSan (UDDT only)							
1	0.9	2.2	-7.5	-1.9	-3.9	-1.3	-1.5
2	2.1	2.9	-2.7	-1.4	-3.8	-0.4	-0.2
3	6.4	5.0	4.6	5.9	0.0	5.2	4.9
4	5.0	2.8	2.3	4.1	-2.3	4.5	3.5
5	3.6	5.8	3.7	4.0	1.1	2.4	3.6
6	1.5	1.1	-2.4	-1.5	-2.2	-0.2	-0.4
7	4.0	5.2	2.2	3.9	0.0	2.1	3.0
8	5.0	4.1	0.0	0.0	0.0	0.0	1.8
9	-0.2	-0.9	0.0	-0.2	0.0	-0.5	-0.4
10	3.0	3.7	-1.2	1.9	-1.7	2.6	1.6
Mean	3.1	3.2	-0.1	1.5	-1.3	1.4	1.6
CaSa (UDDT + oven)							
1	0.9	2.2	-7.5	-1.9	-3.9	-1.3	-1.5
2	1.9	2.8	-2.7	-1.4	-3.8	-0.4	-0.3
3	5.5	6.1	5.8	2.6	0.0	5.5	4.5
4	3.1	3.2	1.0	2.7	-2.3	3.6	2.5
5	0.7	5.4	3.7	1.4	1.1	1.9	2.5
6	1.5	2.1	-8.3	-2.7	-4.2	-1.4	-1.9
7	3.6	5.9	2.2	1.7	0.0	1.9	2.7
8	-3.8	2.0	0.0	0.0	0.0	-1.6	-0.5
9	-0.8	-0.9	0.0	-0.2	0.0	-0.5	-0.5
10	2.7	4.6	-1.2	1.1	-1.7	2.6	1.6
Mean	1.5	3.4	-0.7	0.3	-1.5	1.0	0.9
Septic system							
1	-0.8	-3.7	0.0	-0.5	0.0	-4.7	-1.7
2	-0.3	-5.2	-4.3	-1.1	0.0	-4.8	-2.7
3	1.8	-5.2	-1.4	2.2	0.0	-2.9	-0.9
4	-0.4	-6.5	-3.6	0.6	0.0	-3.4	-2.1
5	0.1	-5.0	-3.9	-1.5	-0.9	-5.2	-2.8
6	0.2	-3.6	0.5	-0.6	0.0	-3.8	-1.3
7	0.6	-6.8	0.8	-1.6	0.0	-8.0	-3.0
8	0.1	-1.4	-1.0	-0.6	-3.3	-1.3	-1.1
9	-1.0	-0.9	0.0	-0.2	0.0	-0.5	-0.6
10	2.6	-1.3	1.3	2.4	1.1	-2.3	0.7
Mean	0.3	-4.0	-1.1	-0.1	-0.3	-3.7	-1.6

Non-common abbreviations: CaSa: Carbonization and Sanitation; EcoSan: Ecological sanitation; SI: Sustainability index; UDDT: Urine-diverting dry toilet; WC: water closet

Table S.9: Results of assessment: 'Individual overall assessment results' of cooking alternatives for ten participants, 'individual weighted scores' aggregated for main-criteria (Eq. A.7) are weighted with relative weights for main-criteria and aggregated to receive the 'individual SI' (Eq. A.8); plot data for Fig. S.5.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria	SI
Charcoal burner							
1	-0.3	-0.4	0.1	0.0	0.0	-0.5	-1.1
2	0.1	-0.3	0.2	-0.1	0.0	-0.1	-0.2
3	0.3	-0.2	0.6	0.4	-0.1	0.4	1.4
4	1.1	0.6	0.2	0.8	0.2	-0.1	2.8
5	0.6	0.0	0.1	0.6	-0.3	-0.2	0.8
6	0.0	-0.4	0.3	0.0	0.0	-0.3	-0.4
7	0.8	0.0	0.0	0.2	-0.6	-0.8	-0.4
8	-0.2	-0.3	-0.6	-0.3	-0.3	-0.2	-1.9
9	0.2	-1.0	-1.0	0.0	0.0	-0.2	-1.9
10	0.8	0.1	0.5	0.8	0.5	0.0	2.8
Mean	0.3	-0.2	0.1	0.2	-0.1	-0.2	0.2
Rocket stove							
1	-0.6	-0.2	0.1	-0.1	0.0	-0.4	-1.2
2	0.9	0.1	0.4	0.0	0.1	0.4	1.8
3	0.5	0.3	0.8	0.6	0.0	0.5	2.6
4	1.1	0.9	0.4	0.6	0.0	0.0	3.0
5	0.7	0.4	0.5	0.8	0.1	-0.1	2.4
6	-0.1	-0.2	0.3	0.0	0.0	-0.5	-0.5
7	0.9	0.5	0.3	0.4	0.4	-0.6	1.7
8	-0.1	0.0	-0.4	-0.3	-0.3	-0.2	-1.2
9	0.1	-0.4	-1.0	0.0	0.0	-0.2	-1.4
10	1.2	0.3	0.7	0.8	0.5	0.2	3.6
Mean	0.5	0.2	0.2	0.3	0.1	-0.1	1.1
Microgasifier							
1	-0.5	-0.2	0.1	0.1	0.0	-0.4	-0.9
2	0.8	0.1	0.2	0.1	0.1	0.4	1.8
3	0.4	0.6	0.8	0.2	0.0	0.7	2.6
4	0.7	1.2	0.3	0.5	0.0	0.1	2.9
5	0.3	0.7	0.1	0.2	0.1	0.2	1.6
6	-0.1	-0.2	0.3	0.1	0.0	-0.5	-0.4
7	0.8	0.7	0.3	0.3	0.4	-0.6	1.8
8	-0.1	-0.2	0.0	-0.8	-0.6	-0.2	-1.9
9	0.1	-0.8	-0.6	0.0	0.0	-0.2	-1.5
10	0.7	0.3	0.7	0.8	0.5	0.3	3.3
Mean	0.3	0.2	0.2	0.2	0.1	0.0	0.9
Biogas system							
1	-0.3	-0.1	-0.1	0.2	0.0	-0.3	-0.6
2	0.7	0.6	0.0	0.0	0.1	0.4	1.8
3	-0.5	-0.3	0.5	-0.3	0.0	0.1	-0.6
4	-0.5	-0.4	0.2	0.5	0.0	-0.2	-0.3
5	-0.5	-0.7	0.0	-0.3	0.1	-0.1	-1.4
6	-0.4	-0.1	0.0	0.1	0.0	-0.3	-0.8
7	0.0	-0.1	0.3	0.1	0.5	-1.2	-0.3
8	-0.1	0.0	0.1	0.0	-0.2	-0.1	-0.4
9	0.1	0.5	0.0	0.1	0.0	0.0	0.8
10	0.6	0.5	0.8	0.6	0.5	0.1	3.2
Mean	-0.1	0.0	0.2	0.1	0.1	-0.2	0.1

Non-common abbreviations: SI: Sustainability index

Table S.10: Results of assessment: 'Individual overall assessment results' of sanitation alternatives for ten participants, 'individual weighted scores' aggregated for main-criteria (Eq. A.7) are weighted with relative weights for main-criteria and aggregated to receive the 'individual SI' (Eq. A.8); plot data for Fig. S.7.

	1) Technological / operational criteria	2) Environmental criteria	3) Health / hygiene criteria	4) Socio-cultural criteria	5) Political / legal criteria	6) Socio-economic / financial criteria	SI
EcoSan (UDDT only)							
1	0.2	0.5	-1.1	-0.3	-0.5	-0.2	-1.5
2	0.4	0.6	-0.5	-0.3	-0.4	-0.1	-0.2
3	1.3	1.1	0.7	1.2	0.0	0.7	4.9
4	1.2	0.6	0.3	1.1	-0.1	0.4	3.5
5	0.6	1.0	0.7	0.8	0.1	0.4	3.6
6	0.3	0.3	-0.5	-0.2	-0.2	0.0	-0.4
7	0.8	1.0	0.2	0.5	0.0	0.4	3.0
8	0.9	0.9	0.0	0.0	0.0	0.0	1.8
9	0.0	-0.3	0.0	0.0	0.0	-0.1	-0.4
10	0.5	0.8	-0.2	0.4	-0.2	0.4	1.6
Mean	0.6	0.6	0.0	0.3	-0.1	0.2	1.6
CaSa (UDDT + oven)							
1	0.2	0.5	-1.1	-0.3	-0.5	-0.2	-1.5
2	0.3	0.6	-0.5	-0.3	-0.4	-0.1	-0.3
3	1.1	1.3	0.9	0.5	0.0	0.7	4.5
4	0.8	0.7	0.1	0.7	-0.1	0.3	2.5
5	0.1	1.0	0.7	0.3	0.1	0.3	2.5
6	0.3	0.5	-1.8	-0.3	-0.4	-0.2	-1.9
7	0.7	1.1	0.2	0.2	0.0	0.4	2.7
8	-0.7	0.4	0.0	0.0	0.0	-0.2	-0.5
9	-0.1	-0.3	0.0	0.0	0.0	-0.1	-0.5
10	0.5	1.0	-0.2	0.2	-0.2	0.4	1.6
Mean	0.3	0.7	-0.2	0.1	-0.2	0.1	0.9
Septic system							
1	-0.2	-0.8	0.0	-0.1	0.0	-0.7	-1.7
2	-0.1	-1.1	-0.7	-0.2	0.0	-0.7	-2.7
3	0.4	-1.1	-0.2	0.5	0.0	-0.4	-0.9
4	-0.1	-1.4	-0.5	0.2	0.0	-0.3	-2.1
5	0.0	-0.9	-0.7	-0.3	-0.1	-0.8	-2.8
6	0.0	-0.8	0.1	-0.1	0.0	-0.5	-1.3
7	0.1	-1.3	0.1	-0.2	0.0	-1.7	-3.0
8	0.0	-0.3	-0.2	-0.1	-0.4	-0.1	-1.1
9	-0.1	-0.3	0.0	0.0	0.0	-0.1	-0.6
10	0.5	-0.3	0.2	0.5	0.1	-0.3	0.7
Mean	0.1	-0.8	-0.2	0.0	0.0	-0.6	-1.6

Non-common abbreviations: CaSa: Carbonization and Sanitation; EcoSan: Ecological sanitation; SI: Sustainability index; UDDT: Urine-diverting dry toilet

S5: Supplement of Section 7.3 of the main text of the thesis '*Valuing Wastes*'

SUPPLEMENTARY MATERIALS OF

Section 7.3: Opportunities and challenges identified for real-world application

A. Krause
Correspondence to: Ariane Krause (krause@ztg.tu-berlin.de)

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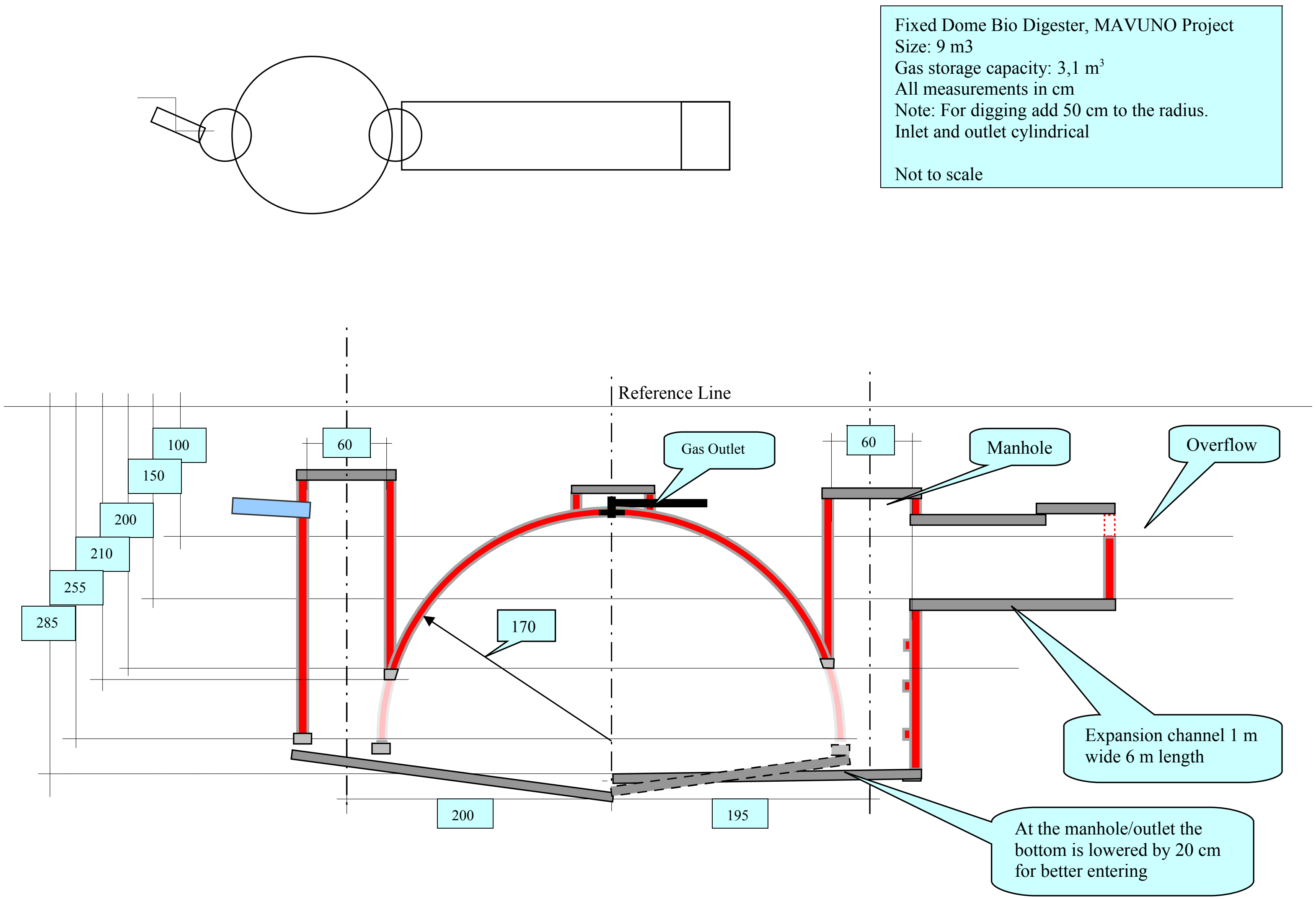

Fig. S5.1: Design of the biogas digester as it is implemented in Karagwe since 2016; after evaluating the technology in 2016, the design was adjusted to the design of a fixed-dome digester type by MAVUNO in cooperation with the Tanzanian Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC) and Engineers Without Borders (EWB) Germany.
[Drawing kindly provided by A. Bitakwate, leader of BiogaST project.]

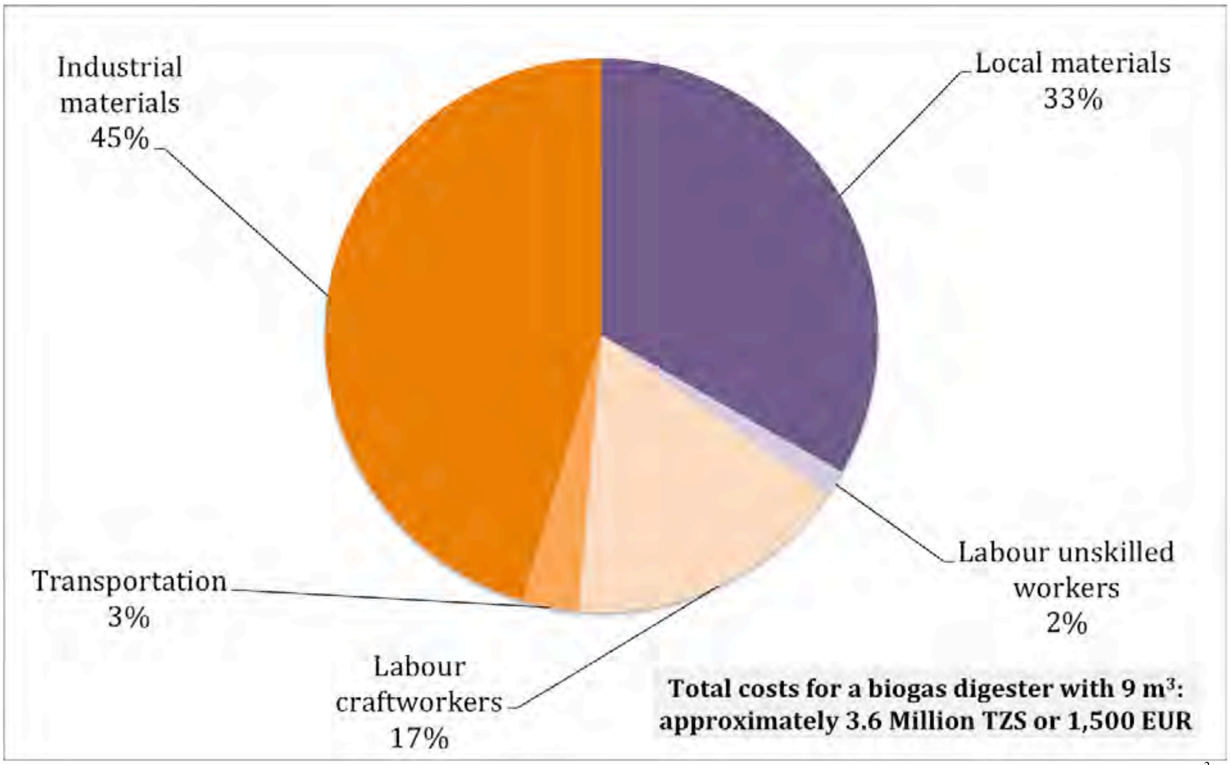

Fig. S5.2: Distribution of total costs for implementing a biogas digester pursuant to the fixed dome design (Fig. A7.1) with a size of 9 m^3: Costs indicated in orange (i.e. 'industrial material', 'transportation', and 'labour craft workers') are covered by funds from external donors and costs indicated in purple (i.e. 'local materials' and 'labour unskilled workers') need to be contributed by customers/farmers. [Data kindly provided by A. Bitakwate, leader of BiogaST project.]

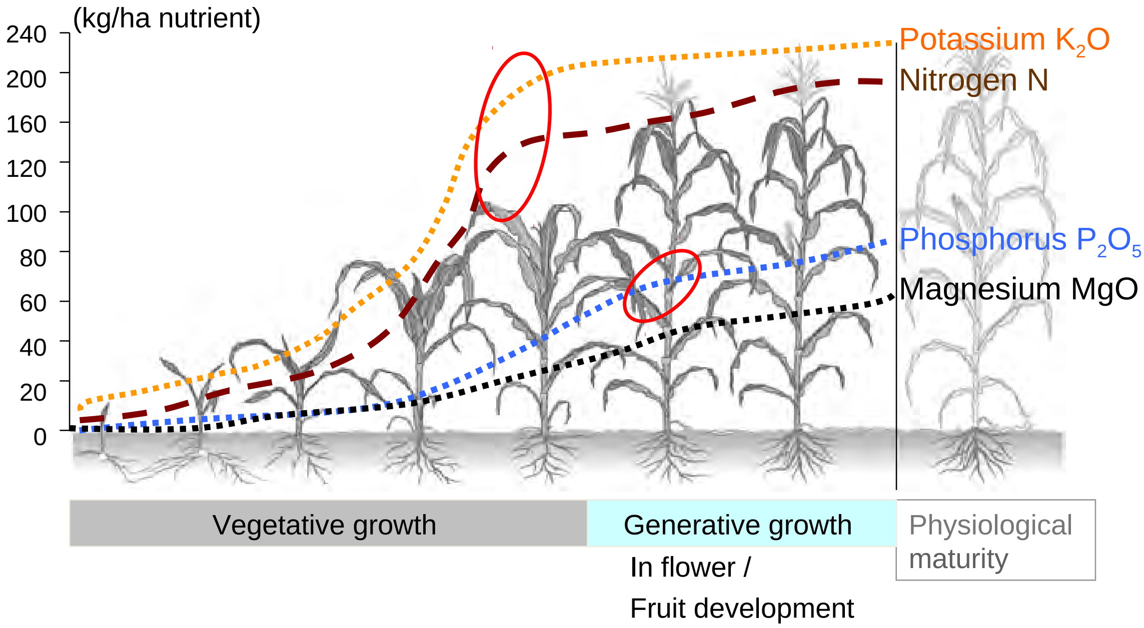

Fig. S5.3: Nutrient demand changes during plant development: uptake of macro-nutrients (indicated on y-axis in kg per ha) during growth (indicated on x-axis by certain development stages of the plant over time) shown for the example of maize plants (Perner et al., 2013).

Fig. S5.4: Pictures of cook stoves that uses fossil gas stove and that are available in shops in the town Kayanga in Karagwe.
[Picture taken by S. Bissett in May 2017.]

Fig. S5.5: Pictures of an extended version of the ‘Kon-Tiki’ cone kiln as a sanitation facility: the `Kon-Tiki’ flame curtain kiln is made of steel and has an outlet pipe at the bottom to drain the quench water (left side; without rim shield); the kiln was constructed in Karagwe in 2016 after instructions that were kindly provided by H. P. Schmidt from the Ithaka Institute; the sanitation `Kon-Tiki’ is augmented with a swivel grate that can be moved sideways alongside the horizontal bar and up and down by using a chain jack/pulley (right side; with rim shield).
[Pictures taken by A. Bitakwate in April 2016.]


Fig. S5.6: Picture of an orchard, or ‘fruit forest’, including papaya, mango, and bananas trees, created by staff members of the CaSa project in 2015 and 2016 by using faeces collected from urine-diverting dry toilets (UDDTs) that are part of a school infrastructure.
[Picture taken by A. Bitakwate in May 2017.]


Fig. S5.7: Picture of passion orchard created by staff members of the CaSa project in 2015 and 2016 by using faeces collected from UDDTs that are part of a school infrastructure. [Picture taken by A. Bitakwate in May 2017.]

TABLES

Table S5.1: Contents of total P (P_{tot}), total N (N_{tot}), and mineral N (N_{min}) in dry mater (DM) of various materials measured in two experiments conducted in Karagwe/Tanzania (experiment 1; Krause et al., 2016) and Großbeeren/Germans (experiment 2; Krause and Klomfaß, 2015) compared with literature data (Meinzinger, 2010)

	Experiment 1	Experiment 2	Literature data	Experiment 1	Experiment 2	Literature data
Material analyzed	P_{tot} g kg^{-1} of DM		P_{tot} g kg^{-1} of DM	N_{min} g kg^{-1} of DM		N_{tot} g kg^{-1} of DM
Faecal compost	3.2	1.8-2.5 [1]		0.4	0.4-0.6	
Standard compost	1.2	0.9		0.1	0.2	
Faecs, dried and sanitized	ua.	14.3	6.4 [2]	ua.	ua.	
Gras	1.0	3.2		ua.	ua.	
Miscanthus	ua.	1.0		ua.	ua.	
Kitchen waste (vegetables and fruits)	ua.	2.9	4.4±1.1	ua.	ua.	19.4±5.2

[1] Value depends on the volumetric share of faeces added to the compost; higher value refers to 40 vol.-% and the lower value to 20 vol.-% of the total mixture.
[2] Calculated from 0.4 g P p^{-1} d^{-1} in faeces in FM of 250 g p^{-1} d^{-1} with a DM-content of 25 % in FM equals faeces in DM of 62.5 g p^{-1} d^{-1}.
Same methods used for analysis in both experiments which include:

- P tot measured after nitric acid (HNO_3) digestion under pressure
- N_{min} extracted with potassium chloride (KCl) and analyzed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany) in Tanzania, and a probe at IGZ.

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LIST OF ABBREVIATIONS

CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
DM	Dry matter
EWB	Engineers Without Borders
N	Nitrogen
N_{min}	Mineral N
N_{tot}	Total N
P	Phosphorus
P_{tot}	Total P
UDDT	Urine-diverting dry toilet