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Linking energy-sanitation-agriculture: Intersectional resource management in smallholder households in Tanzania

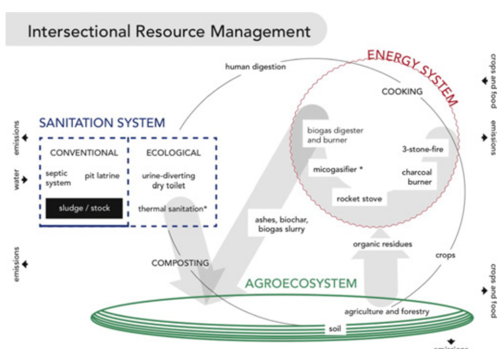
Ariane Krause [a,*], Vera Susanne Rotter [b]

[a] Technische Universität (TU) Berlin, Postgraduate program "Microenergy Systems", Center for Technology and Society, Office HBS1, Hardenbergstr. 16–18, 10623 Berlin, Germany
[b] TU Berlin, Department of Environmental Technology, Chair of Circular Economy and Recycling Technology, Office Z2, Straße des 17. Juni 135, 10623 Berlin, Germany

HIGHLIGHTS

- Residues from cooking and sanitation can contribute effectively to soil fertility management.
- Resource recovery can substantially promote carbon and nutrient recovery.
- Study includes an application of intersectional resource management to vulnerable smallholders in SSA.
- Study includes model-based analyses of technology specific material flows at a household level.
- Study provides aggregated data sets including empirical data from Tanzania.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to create sustainable systems for resource management, residues from cooking and ecological sanitation (EcoSan) can be employed in recycling-driven soil fertility management. However, the link between energy, sanitation, and agricultural productivity is often neglected. Hence, the potential self-sufficient nature of many smallholdings in sub-Saharan Africa is underexploited.
Objective: To compare those cooking and sanitation technologies most commonly used in north-western Tanzania with locally developed alternatives, with respect to (i) resource consumption, (ii) potential to recover resources, and (iii) environmental emissions. This study examines technologies at the household level, and was carried out using material flow analysis (MFA). The specific bioenergy technologies analysed include: three-stone fires; charcoal burners; improved cooking stoves (ICS), such as rocket and microgasifier stoves; and biogas systems. The specific sanitation alternatives studied comprise: pit latrines; two approaches to EcoSan; and septic systems.
Results: The use of ICS reduces total resource consumption; using charcoal or biogas does not. The residues from microgasifiers were analysed as having a substantial recovery potential for carbon (C) and phosphorus (P). The fact that input substrates for biogas digesters are post-agricultural in nature means that biogas slurry is not considered an 'untapped resource' despite its ample nutrient content.
Exchanging pit latrines for water-based sanitation systems places heavy pressure on already scarce water resources for local smallholders. In contrast, the implementation of waterless EcoSan facilities significantly promotes nutrient recovery and reduces environmental emissions, particularly through greenhouse gas emission and nutrient leaching.

* Corresponding author.
E-mail addresses: krause@ztg.tu-berlin.de (A. Krause), vera.rotter@tu-berlin.de (V.S. Rotter).

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Conclusions: Recycled outputs from the triple energy-sanitation-agriculture nexus display complementary benefits: residues from cooking can be used to restore organic matter in soils, while sanitation residues contribute to fertilisation. The combination of microgasifiers and EcoSan-facilities is the most appropriate in order to simultaneously optimise resource consumption, reduce environmental impacts, and maximise recycling-based soil management in smallholder farming systems.

1. Introduction

1.1. The energy-sanitation-agriculture nexus

In many regions of the world, including sub-Saharan Africa (SSA), biomass is the most significant energy carrier for domestic cooking (Parikka, 2004). In this context, "bioenergy" refers to the technical recovery of energy from biomass resources, such as firewood, organic waste, energy plants, etc. (Kaltschmitt et al., 2009). To avoid exhausting natural resources, it is necessary to manage biomass resources effectively, both in its collection, and its efficient use. The former is realised through sustainable resource management techniques, such as forestry management. The latter is achieved largely through employing well-designed technology, such as those for cooking. The simplest and most prominent application of bioenergy is likely to be the three-stone fire. There are, however, more environmentally friendly, technologically sophisticated bioenergy alternatives available that have been designed with the aim of reducing, or substituting, the use of firewood. These include improved cooking stoves (ICS), which use firewood or organic waste materials with a low moisture content, such as sawdust, maize cobs, rice husks, coffee husks, etc. ICSs are employed to provide heat for cooking in both households and institutions (Jetter and Kariher, 2009; Mukunda et al., 2010). So-called microgasifier stoves are a particularly technologically advanced example of ICS (Roth, 2011). After cooking with a microgasifier stove, a mix of ash and char particles with a significant carbon (C) content is produced as a by-product (McLaughlin et al., 2009). Referred to as 'biochar,' it can be used as an additive for compost (Kammann et al., 2015) and thus as a soil amendment (Lehmann and Joseph, 2015), after the principles of the genesis of Terra Preta soils (Glaser and Birk, 2012). Organic matter with comparatively higher moisture content, meanwhile, such as cow dung, kitchen waste, harvest residues, etc., can be anaerobically fermented in small-scale biogas digesters (Tumwesige et al., 2011; Vögeli et al., 2014). The residue of biogas production, biogas slurry (also called bio-slurry or digestate), is particularly rich in nutrients and is a suitable fertilizer in organic farming (Möller and Müller, 2012). To sum up, depending on the availability of the respective fuel resources, bioenergy technologies can (i) substitute firewood as the main energy carrier, which reduces pressure on forest resources, and (ii) provide residues, which can in turn be used to recover nutrients and C for agriculture.

Bioenergy can also be applied to sanitation processes in order to destroy or deactivate pathogens from human excreta (Krause et al., 2015). Preventing the transmission of disease when managing human excreta (i.e. urine and faeces) is an essential element of ecological sanitation (EcoSan) and needs to take place at as early a stage as possible during the process (WHO, 2006). For this reason, thermal sanitation must take place *directly* after the faeces, which have the highest pathogen content, have been collected in a urine-diverting dry toilet (UDDT) or composting toilet, and *before* the matter is composted. Thermal sanitation follows the time-temperature relationship to deactivate pathogens as described by Feachem et al. (1983), and is realised in practice via pasteurisation (Krause et al., 2015), co-pelletising with subsequent gasification (Englund et al., 2016), or direct incineration (Niwagaba et al., 2009). Further approaches for sanitation include drying (Richert et al., 2010), composting (Ogwang et al., 2012), or lacto-acid fermentation (Factura et al., 2010). Sanitising urine, in contrast, is relatively easy and safe. The World Health Organisation recommends simply storing it, which leads to a rise in pH that inactivates pathogens (WHO, 2006). Once sanitation has been completed, human excreta constitutes a valuable resource of nitrogen (N), phosphorus (P), potassium, and micronutrients. Against this background, within the framework of EcoSan, human excreta is no longer regarded as 'waste' but rather as a resource. To sum up, EcoSan is an alternative to conventional 'one-way' or 'end-of-pipe' sanitation systems which aims to (i) prevent environmental pollution, especially that of aquatic ecosystems, and (ii) recycle resources, including the nutrients in human excreta and wastewater (Esrey et al., 2001; Winblad et al., 2004).

1.2. Research objectives & questions

The prime source of energy in Tanzania (TZ) is wood, either utilised directly as firewood, or in the form of processed charcoal (Msuya et al., 2011). When looking at farming households in rural TZ, meanwhile, we find a variety of different biomasses used as cooking fuels, though firewood still clearly dominates (Grimsby et al., 2016). Furthermore, while septic systems are most common in peri-urban and urban areas, pit latrines are the most common sanitation system in rural areas (Chaggu, 2004; Cheruiyot and Muhandiki, 2014). The widespread installation of pit latrines from the 1940s, largely through 'development cooperation', has led to the abandonment of locally adapted recycling practices (Rugalema et al., 1994). This means that those nutrients removed from the soil by crops are no longer fully recycled back into the agricultural soils. The result of this is that depletion of nutrients and soil organic matter (SOM) is, alongside erosion, a major threat to smallholder farming in SSA (Markwei et al., 2008; Montanarella et al., 2016). As mentioned above, residues from bioenergy and EcoSan are a potential resources to recover C for restoring SOM and nutrients, thereby filling the fertiliser gap.

To the best of knowledge, there have been as yet no *integrated* resource studies carried out that combine an analysis of both applied cooking and sanitation technologies in relation to smallholder households in SSA. It is the aim of the present work to develop a model that enables an assessment of the added benefits intersectional resource management could bring to a model region in north-western TZ. The study was conducted on a micro-level, i.e. on a household level, and is presented with three specific projects as case studies. The objective was to compare *locally available* cooking and sanitation technologies in regards to (i) resource consumption, (ii) potential for resource recovery for use in agriculture (i.e. ash, biochar, biogas, slurry, and human excreta, as well as the nutrients and C contained therein), and (iii) environmental emissions. In order to meet this objective, we identified, quantified, visualised, and evaluated technology-specific material flows within the anthroposphere of a smallholder farming system in TZ. Negative effects on the ecosystem were assessed using global warming potential (GWP) and eutrophication potential (EP). It is our aim through this study to (i) advance the practical application of bioenergy and EcoSan technologies in SSA, and (ii) promote the recycling of resources through established methods, including agroecology, composting, integrated plant nutrient management, and Terra-Preta practices.

We identified our underlying research questions as follows: (Q1) How do locally available bioenergy alternative, such as rocket stoves, microgasifiers, and biogas systems, compare to more widespread