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Full Length Research Paper

Nutrient recycling from sanitation and energy systems to the agroecosystem- Ecological research on case studies in Karagwe, Tanzania

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Open cycles of organic carbon and nutrients cause soil degradation. Procedures such as ecological sanitation (EcoSan), bioenergy and Terra Preta practice (TPP) can contribute to closing nutrient cycles and may, in addition, sequester carbon. This paper introduces three projects in Karagwe, Tanzania, and their applied approach of integrated resource management to capture carbon and nutrients from different waste flows. Substrates derived from these case studies, biogas slurry, compost and CaSa-compost (containing biochar and sanitized human excreta), were assessed for their nutrient content by analysis of the total element composition. Evaluation focused on potential impacts of the tested amendments on the nutrient availability in the soil as well as on the local soil nutrient balance. Results revealed that all substrates show appropriate fertilizing potential compared to literature, especially for phosphorus (P). CaSa-compost was outstanding, with a total P concentration of 1.7 g dm^{-3} compared to 0.5 and 0.3 g dm^{-3} in compost and biogas slurry respectively. Furthermore, these soil amendments may reduce acidity of the soil, with a calculated liming effect of 3.4, 2.6 and 7.8 kg CaO for each kg of nitrogen added for biogas slurry, compost and CaSa-compost respectively. To offset negative P balances in Karagwe, about 8100, 6000 and 1600 dm^3 ha^{-1} are required for biogas slurry, compost and CaSa-compost respectively. We conclude that especially CaSa-compost might offer immediate positive effects to crop production and nutrient availability in the soil.

Key words: Ecological sanitation, bioenergy, Terra Preta practice, biochar, biogas slurry, compost, soil amendments, soil improvement, waste as resource.

INTRODUCTION

Open cycles cause agronomic problems

Since more nutrients are taken out of the agroecosystem than are put back, anthropogenic activities create open cycles of mineral nutrients and carbon (C) (Lal, 2006). Such activities comprise among others: Excessive

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deforestation for firewood, exploitation of phosphate rocks for fertilizer production, and energy consumption for production of synthetic fertilizers. Furthermore, most current sanitation systems waste nutrients from human excreta (especially nitrogen (N), phosphorus (P) and potassium (K) as well as micronutrients) since they are either disposed in the ground (pit latrine, ashes of incinerated sewage sludge) or enter the aquatic system (pit latrine, flush toilet), where they cause eutrophication and lead to contamination of the groundwater with fecal microorganisms(Esrey et al., 2001;Graham and Polizzotto, 2012; Meinzinger, 2010). In general, open cycles can cause soil degradation and loss of soil fertility since cultivated soils become increasingly deficient in essential plant nutrients when long term cropping takes place without replacement of nutrients (Hartemink and Bridges, 1995). In addition, soil organic matter (SOM), which is the major building block of a fertile soil, might be depleted by continuous cropping if the plant residues are not put back into the soil after harvesting (Batjes and Sombroek, 1997). Consequently, the soil might show declining water and nutrient retention capacity and an increasing tendency to soil erosion (Horn et al., 2010). Tropical climate conditions aggravate such soil degradation; with year-round elevated temperature, SOM is lost due to fast microbial decomposition of organic matter; heavy rains during the rainy season in turn cause leaching of mineral nutrients (Lal, 2009). It is widely agreed that in order to secure sustainable food supply for everyone, soil degradation must be reversed and soil productivity enhanced.

Problems of using synthetic fertilizers in Sub-Saharan Africa

Agricultural practices using synthetic fertilizers often add too much N to the soil and sometimes neglect input of P, K and micronutrients, which can result in imbalanced plant nutrition (Lal, 2009). Furthermore, nutrients added by synthetic fertilizers often are immediately available and thus can be subject to high losses via leaching and volatilization (Finck, 2007; Savci, 2012). Moreover, the *International Assessment of Agricultural Knowledge, Science and Technology for Development* (IAASTD) showed that in some parts of Sub-Saharan Africa (SSA), especially poor farmers do not have access to synthetic fertilizers (Markwei et al., 2008). Those who have access often lack adequate information on their appropriate use (*ibid.)*. Inappropriate use of synthetic fertilizers, however, may result in soil acidification, pollution of water bodies, and emissions with global warming potential to the atmosphere (Markwei et al., 2008; Savci, 2012). Furthermore, the production of synthetic fertilizers requires energy; for example about one third of the total energy input to crop production of the United States of America is required to produce, to package, to transport and to apply synthetic fertilizers (Gellings and Parmenter, 2004).

Solutions based on using locally available organic fertilizers

Kiers et al. (2008) concluded that in African countries reversing soil infertility might be achieved “through the use of locally available resources”, because the use of synthetic fertilizers is not a feasible option for many subsistence farmers. In “Agriculture at a crossroads“ McIntyre et al. (2009) called for a focus on efficient, small-scale agroecosystems with almost closed nutrient cycles. In addition, the IAASTD demanded that research in a SSA context should reorient “towards integrated nutrient management approaches” (Markwei et al., 2008). Kimetu et al. (2004) demonstrated in Western Kenya that “inorganic N additions can be fully substituted by organic N additions if the appropriate source of organic matter is applied”. Furthermore, the intensified use of organic fertilizer can reduce the cost of fertilization in crop production in SSA (Markwei et al., 2008).

In order to create positive C and nutrient budgets, SOM can be enhanced through addition of organic amendments, as Lal (2009) pointed out. He further suggested that both organic residues, such as compost and animal manures, and biological N-fixation should be included in the nutrient management (*ibid.*). Stoorvogel (1993) particularly emphasized the efficient use of organic household waste as a means to supply nutrients. Beardsley (2011) pointed out that human excreta “is an abundant but often ignored source of P available for recycling worldwide”. Another important soil management practice to strengthen the nutrient cycling process in SSA is acidity management through liming, as described, for example, by Batjes and Sombroek (1997).

Approaches towards closing the loop

In our research, we focus on the following practices for local nutrient and C recycling: (1) Composting in general, as well as co-composting of human excreta and ecological sanitation (EcoSan); (2) Provision of bioenergy combined with agricultural use of residues; (3) Terra Preta practices (TPP) – using biochar as a soil amendment.

Composting and ecological sanitation

Composting is a globally common method in agriculture whereby organic residues are mixed with mineral components and subsequently aerobically decomposed by macro- and microorganisms (for East-Africa see work of e.g. Amoding et al. (2005), Karungi et al. (2010) and

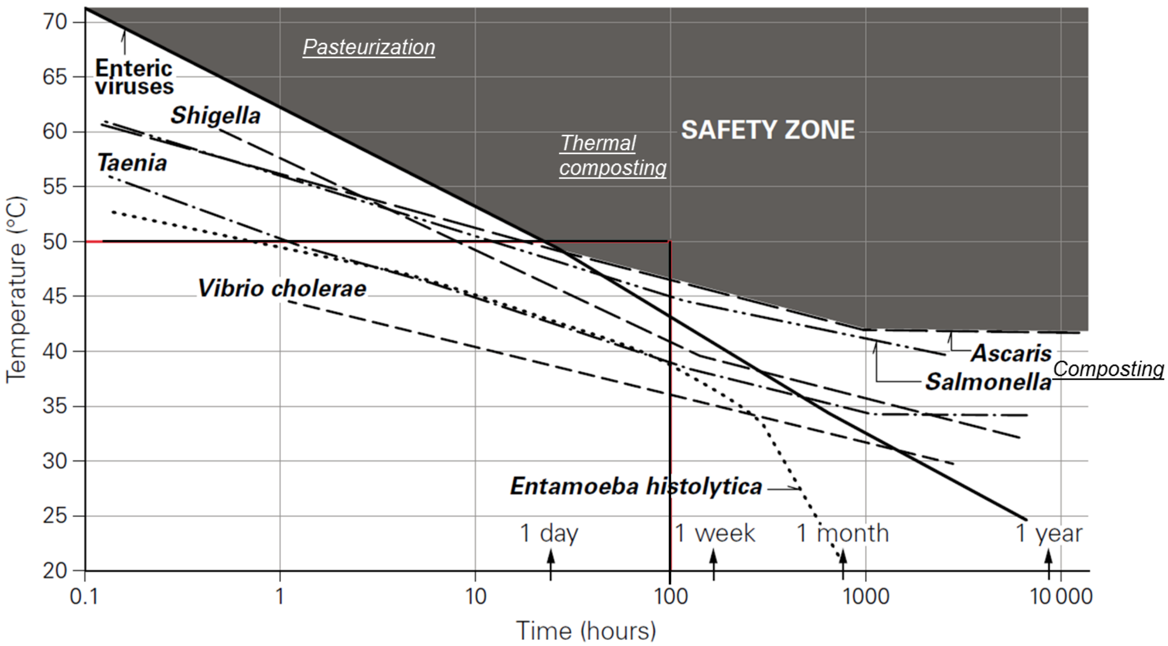

Figure 1. Relationship between temperature and time required to inactivate certain pathogens (according to Feachem et al., 1983, graphic adopted from Vögeli et al., 2014; corresponding combinations of time and temperature for the described possible treatments are indicated)

Tumuhairwe et al. (2009). EcoSan facilitates co-composting of human excreta as an alternative to conventional sanitation systems. EcoSan aims at (i) "closing the loop" by recycling nutrients from humanexcreta in order to improve soil fertility; (ii) avoiding potential human health risks by sanitizing urine and feces; (iii) preventing the pollution of freshwater and marine environments by avoiding waste water discharge into natural water bodies (Winblad et al., 2004). Further benefits of EcoSan, according to Esrey et al. (2001), are that it is: (i) A decentralized system based on household and community management and, thus, omits investment in large-scale infrastructure; (ii) Particularly appropriate in areas with water shortages or irregular water supply since no or very little water is required; (iii) Feasible in both rural and urban areas as well as for rich and poor people alike. Usually, urine and feces are stored and processed on-site. A number of different types of composting toilets are in use in EcoSan, e.g. the urine diverting dry toilet (UDDT), which collects human excreta separately (see Morgan, 2007, for further description and discussion of "Toilets That Make Compost - Low-cost, sanitary toilets that produce valuable compost for crops in an African context"). According to the World Health Organization (WHO, 2006) urine is safe for use as a fertilizer, untreated or after short storage. However, feces mostly contain pathogens (such as viruses, bacteria and worm eggs) and require treatment (*ibid*.). Techniques for sanitation include: dehydration or drying, e.g. through UDDT with a separation of the solid parts and the liquid fraction of the excreta and improved ventilation system (Winblad et al., 2004); disinfection by using additives, e.g. urea (Vinnerås, 2002) or lactic acid bacteria (Factura et al., 2010); disinfection through exposure to elevated temperatures over time, e.g. mesophilic or thermophilic composting (Niwagaba et al., 2009; Ogwang et al., 2012) or pasteurization (RKI, 2013; Schönning and Stenström, 2004). In general, thermal sanitation relies on a temperature/time relationship to inactivate certain pathogens, as described by Feachem et al. (1983) (Figure 1).

Currently, there are no national regulations for the treatment of human excreta, in neither Tanzania nor Germany, but different guidelines for thermophilic composting exist. The WHO (2006) recommended a treatment at 55 to 60°C over several days up to one month depending on the conditions (e.g. constant control of the temperature). In Germany, the following thermal treatments are required for organic waste in general: 55°C for two weeks, 60°C for six days or 65°C for three days (German BO, 2013).

Bioenergy and the agricultural use of its residues

Bioenergy technologies focus on energy recovery from biomass. Also, by-products and residues from bioenergy provision can be recycled back into the agroecosystem. The main principle is the conversion of biomass to heat for either the consecutive production of electricity or direct provision for productive processes (e.g. for a bakery, green-house heating) and consumption in households or institutions (e.g. for cooking and heating) (Kaltschmitt et al., 2009). In this study, our focus is onprovision of cooking energy at household level and the applied technologies include: three stone fire, charcoal burner, microgasifier and a system using a biogas digester and biogas burner. The use of firewood, three stone fires and charcoal burners is currently most common in many countries of SSA. Ash is the main residue from these bioenergy applications and contains mineral nutrients such as P and K as well as calcium (Ca) and magnesium (Mg), but hardly any C, N or sulphur (S) since these elements volatilize during the oxidation process. Ash is therefore often used as a soil amendment or addition to compost. Another small-scale technology is the biogas digester, which is used for cooking both in households and institutions, such as schools or hospitals (Vögeli et al., 2014). Organic wastes are anaerobically digested via microbiological activity in a closed fermenter, resulting in a methane-rich combustible gas as the main product and biogas slurry as a liquid residue (*ibid*.). Small-scale and low-tech biogas digesters usually operate in a mesophilic range of about 30 to 40°C and a retention time of around 40 days (Kossmann *et al.*, undated). Biogas is accumulated inside the digester or in a separate storage tank and is usually combusted in a biogas burner. Biogas slurry can be used as a fertilizer since it contains most of the mineral nutrients from the digested organic waste in an already plant-available form (Vögeli et al., 2014). Caution and additional treatment of the biogas slurry is required, however, in case human excreta is also digested since pathogens are not inactivated under the mesophilic conditions mentioned above (Figure 1). In Nepal, for example, Lohri et al. (2010) showed that the biogas slurry from mixed fermentation of human excreta and kitchen waste contained pathogens such as helminth eggs. Moreover, inappropriate use of the liquid biogas slurry can cause eutrophication if it is applied in excess or discharged directly to a receiving body of water (Kossmann et al., undated). Finally, households can meet their energy demand by using microgasifiers, which are improved cooking stoves that use dry biomass and spatially separate the transformation of biomass into combustible wood-gas from the subsequent oxidation of the gas (Mukunda et al., 2010; Roth, 2013). One particularly prominent stove design is called the TLUD ("Top-Lit Up Draft"), which is licensed as an open source technology (Anderson and Reed, 2007). Apart from heat, the stove provides charcoal of about 10 to 30% of the fuel fresh weight as a by-product (Roth, 2013). As for ash, charcoal preserves mineral nutrients. It also contains C in a concentration of about 60 to 75% of its dry matter (DM) (McLaughlin et al., 2009). The charcoal can be used for further provision of energy by directly pouring the hot charcoal onto a conventional charcoal burner, to continue cooking immediately, or by making charcoal briquettes in a separate process with an accumulated amount of charcoal. Charcoal can also be used as a soil amendment, which is then termed biochar (Taylor, 2010). Altogether, residues from bioenergy processes have a potential for use as soil amendments; however, their quality depends on the composition of the feedstock used and the application practice. There is a need for field experiments to evaluate the impact of biogas slurry on the local carbon balance as well as on soil characteristics and productivity (Bogdanski and di Caracalla, 2011). The positive effects of pyrolitic charcoal as a soil amendment are historically evident in findings of Terra Preta soils, which we will introduce in the following section. However, there is still a lack of scientifically rigorous field experiments using biochar derived from microgasifiers on tropical soils.

Terra Preta practices (TPP) - using biochar as a soil amendment

One particularly interesting and promising holistic approach for improving or remediating degraded soils is the principle of "Terra Preta" (Portuguese for "Black Soil" = "Udongo Meusi" in Swahili), as practiced by people in the Amazon basin in Brazil, South America, centuries ago (Sombroek, 1966; Glaser et al., 2002). Lehmann et al. (2003b) classified Terra Preta as Anthrosol, a human-made, fertile, black soil. Glaser and Birk (2012) found that it mainly contains charcoal, animal and human excreta as well as other organic and inorganic wastes. Compared to surrounding soils, including Ferralsol, Acrisol or Arenosol, the Terra Preta soils show significantly higher availability of P, Ca, manganese (Mn), and zinc (Zn) (Lehmann et al., 2003a). For example, Falcão et al. (2009) found up to 40 times larger concentrations of plant-available P in Terra Preta than in surrounding natural soils. Other characteristics include high water and nutrient retention capacity as well as a pH of around 5.7, adequate for plant growth (Lehmann et al., 2003a; Horn et al., 2010). Biochar plays a major role for the specific properties of Terra Preta because it builds up a stable stock of SOM. Biochar shows an aromatic C structure with many micro pores, large surface, high adsorption capacity and a C-concentration of about 70 to 80% of DM (Lehmann and Joseph, 2009). In some soils, biochar can significantly improve the availability of both nutrients and water by effecting chemical and hydraulic characteristics of the soil. It can also positively affect the activities of soil microbial communities (Lehmann and Joseph, 2009; Glaser and Birk, 2012). According to Taylor (2010), biochar works as a catalyst in the soil, because it "facilitates reaction beneficial to soil dynamics without being consumed in the process". This means that much of the biochar persists in the soil and is not decomposed in the way many other organic materials are (*ibid*.). Therefore, biochar amendments may enhance plant growth in some cases, although nutrient inputs from biochar are low (Lehmann and Joseph, 2009).

Consequently, its application was tested in combination with mineral fertilizers (Kimetu et al., 2004; Jeffery et al., 2011), in combination with compost that releases nutrients over time (Liu et al., 2012; Schulz et al., 2013), and as compost-additive to be enriched and loaded with nutrients during the composting process (Kammann et al., 2015).

Recently, Frausin et al. (2014) revealed the presence of so-called African Dark Earth at more than 134 locations in several West-African countries including Liberia, Sierra Leone, Guinea and Ghana. This Terra Preta-like African Anthrosol is preferably located in the vicinity of towns and mainly is the product of women doing appropriate management of wastes from housing and farming (*ibid*.). Altogether, TPP - using biochar as compost-additive and soil amendment - is seen as a “suitable technique helping to refine farm-scale nutrient cycles” (Schulz et al., 2013).

Research objectives

Based on the context described in the introduction, we hypothesize that new approaches which combine EcoSan, bioenergy and TPP can contribute to soil improvement and resource protection by recycling of nutrients and C, if sanitation is taken into account and integrated appropriately. Especially the use of biogas slurry from fermentation of organic waste as a fertilizer and the combined composting of residues from microgasification and sanitized human excreta are promising methods. However, there is need for practice-oriented experiments and assessment of the local ecological impacts under the specific conditions of tropical regions. Hence, the objectives of this paper were (i) to introduce three case studies from Karagwe, Tanzania, and their applied approach of integrated resource management; (ii) to assess the substrates derived from these projects with respect to their nutrient concentrations; and (iii) to evaluate potential impacts of the tested amendments on the nutrient availability in the soil as well as on the local soil nutrient balance.

MATERIALS AND METHODS

Farming activities in Karagwe, Tanzania

Karagwe district is located in Kagera region in northwest Tanzania, a hilly area situated at an altitude of about 1200 m up to 1800 m.a.s.l., semi-arid with equatorial-tropical climate (Baijuka and de Steenhuijsen Piters, 1998). The average daily temperature is about 21°C, with a range from 10°C at night to > 40°C during the daytime (Blösch, 2008). Rainfall is bimodal with rainy seasons from March to May (long rainy season) and October to November (short rainy season), with crop cultivation taking place during both seasons (Tanzania, 2012). Precipitation ranges between 1000 and 2100 mm $a^{-1,}$ with annual and regional differences (Blösch, 2008).

According to the national sample census of agriculture 2007/2008 for Kagera region, most families in Karagwe districtsubsist on farming activities (Tanzania, 2012): about 45% of the population work full-time on their farms and more than 86% of the households sell agricultural products grown on their farms. On average, around 0.75 ha usable land is available per household out of which around 83% is planted. The most important permanent crops are banana and coffee, while beans, sorghum and maize dominate annual cropping. Most of the planted land is used multiply in mixed cropping systems and only some 16% of the land is used for temporary mono-cultural cultivation. A majority of approximately 78% of the farmers in Kagera region who apply fertilizers on their land, use organic fertilizers which are according to Baijukya and de Steenhuijsen Piters (1998) mainly grasses (mulch) and farmyard manure. However, the supplied amount only suffices for roughly 5% of the planted land (distributed to 0.7 and 4.3 %. of the planted land in the long and short rainy season respectively). Synthetic fertilizers are used on less than 1% of the planted land in Kagera region. In 2010 we conducted a preliminary study in Karagwe district including a survey on 10 households and soil sampling at three different farms. We found that small-scale farmers in Karagwe live on an average with six people in one household. In addition, we found that some major problems of local agriculture are a very low soil pH of 3.8 to 4.2, low nutrient availability (especially P) and soil erosion due to a hilly landscape. Concerning sanitation services, a majority of more than 90% of the rural population of Karagwe district use pit latrines, around 6% do not have any toilet so use bushes and only 1% uses flush toilets in combination with septic tanks (Tanzania, 2012). Hence, for 91% of rural households in Karagwe district, excreta are disposed in a pit or tank after dropping without any treatment or use. Concerning energy supply, the most common source of energy for cooking is biomass, with about 96% of the rural households using firewood and 3% using charcoal (Tanzania, 2012). It is common in Karagwe to add ashes from three stone fires to the compost.

Grassroots projects in Karagwe realizing integrated resource management

Since 2008, two local non-governmental organizations, namely MAVUNO Project Improvement for Community Relief and Services (MAVUNO; meaning “harvest” in Swahili) and CHEMA Programme for Community Habitat Environmental Management (CHEMA), have initiated projects in cooperation with the German association Ingenieure ohne Grenzen e.V. (Engineers Without Borders, EWB) and Technische Universität (TU) Berlin. These projects follow a community-participatory approach to appropriate development of technologies and aim at resource protection, autonomous energy supply and safe sanitation services. Together, these projects present an integrated approach to resource management as well as recycling of nutrients and C (Figure 2). Their process combines three systems: The energy system, whereby cooking energy is provided as heat by either burning biogas from a small-scale biogas digester or by microgasifiers; the sanitation system based on EcoSan; finally, the recycling of by-products from both systems, namely biogas slurry, biochar and sanitized human excreta, back into the agroecosystem. In the latter, composting and the principles of TPP are applied to capture nutrients and C from different waste flows.

One of the expected results is soil improvement, to ensure long-term food security and income generation for the rural population. The respective technologies were developed and tested in Karagwe within three pilot projects:

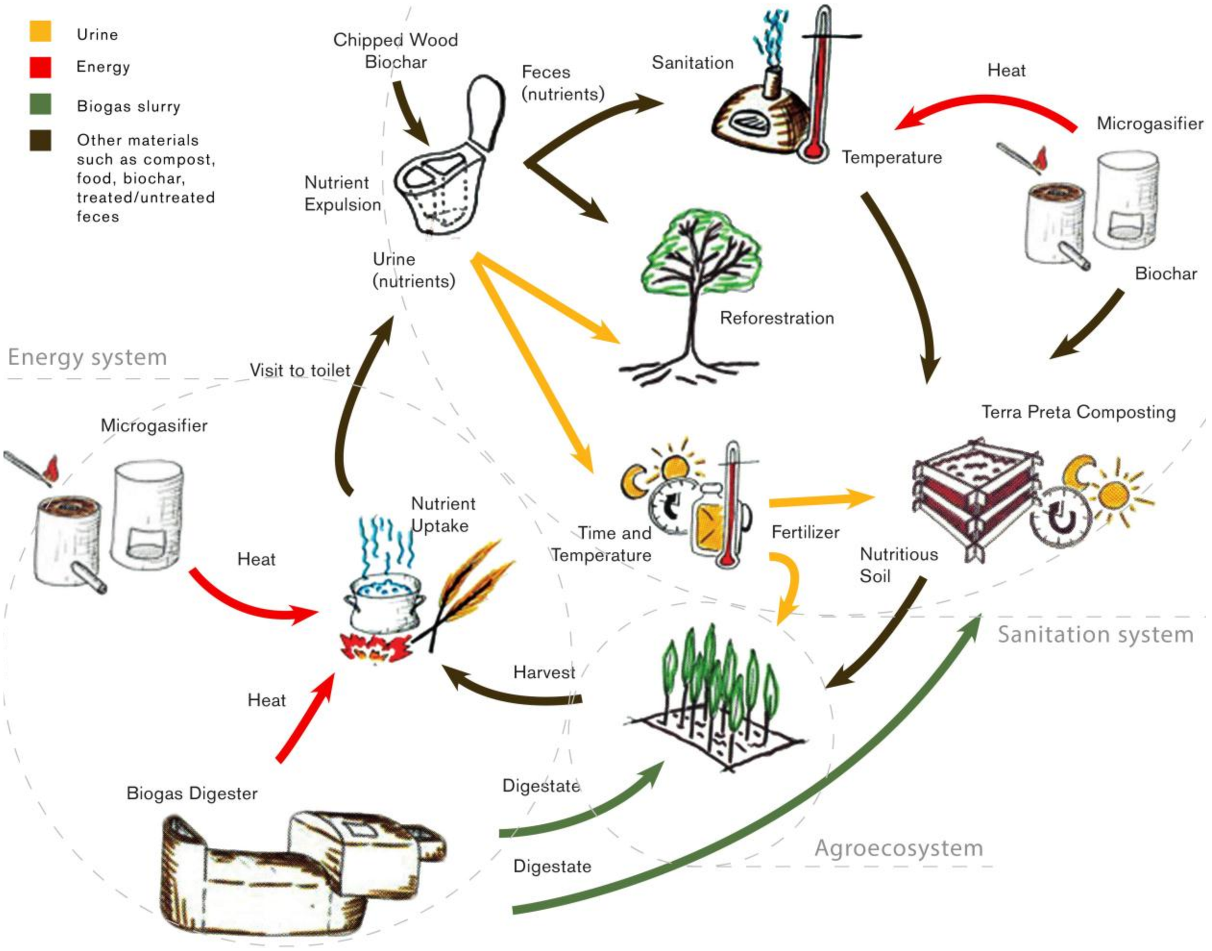

Figure 2. Illustrated concept of the integrated approach of bioenergy, EcoSan, TPP for sustainable food production where waste is considered a resource, as realized by three projects in Karagwe, Tanzania (own picture; with graphical assistance of Daniel Mutz and Lusi Ajonjoli).

(1) The project "Carbonization and Sanitation" (CaSa) aims at closing the cycle of nutrients on a local scale by recycling human excreta without health hazards. This project is a cooperation of MAVUNO, EWB and TU (CaSa, 2011). The approach is called CaSa because the heat of the carbonization process is used for thermal sanitation (Figure 2). The process starts in a UDDT, where a mixture of dry materials like biochar, sawdust, loam soil and ash is added after defecation to improve and accelerate drying of the feces. All solid parts including toilet paper are collected in aluminum pots and remain inside the UDDT for two to four weeks in order to dry. Afterwards, the pot is brought to a loam oven for thermal sanitation via the process of pasteurization, where microgasifiers are used to provide the required heat. Finally, the co-produced biochar, sanitized human feces and stored urine are composted together with other organic and mineral residues. The pilot project for testing the technologies started in 2012 and finished in 2014; since then the implementation has begun with the construction of eight toilets, a sanitation area and a composting area in a boarding school in Karagwe.

(2) The project "Biogas Support for Tanzania" (BiogaST) focuses on the sustainable provision of cooking energy through small-scale biogas digesters, which use organic residues from farming. It is a cooperation of MAVUNO, EWB and the University of Hohenheim in Stuttgart, Germany. The technology follows the design of a plug flow reactor and uses mainly cut pieces of banana tree stump, mixed with cow dung and kitchen waste. Water, together with the anaerobic microorganisms, is recycled and nutrient-rich biogas slurry is produced (Becker and Krause, 2011). Since 2010, two pilot digesters have been in operation to study (i) the effect of using different organic wastes in different mixtures and (ii) the design of a heating system to raise the temperature inside the fermenter and consequently increase biogas production. In 2015, implementation will start with the construction of a larger digester to provide a school canteen with cooking energy.

(3) The project "Efficient Cooking in Tanzania" (EfCoiTa) conducts research on advanced designs of microgasifiers including TLUD and improved sawdust stove (Ndibalema and Berten, 2015). In this project, CHEMA and EWB work in close cooperation with the Center for Research in Energy and Energy Conservation (CREEC) based at Makerere University and Awamu Biomass Energy Ltd, both located in Kampala, Uganda. In 2014, a series of so-called water boiling tests were performed to assess the resource efficiency and currently, in 2015, so-called controlled cooking tests are in progress together with kitchen performance tests to evaluate the practical use of the stoves in local households (Ndibalema and Berten, 2015).

Technically, these projects are connected through the use of microgasifiers for thermal cooking energy in the EfCoiTa-project as well as for the sanitation process in the CaSa-project. Furthermore, they collectively consider waste as a resource and exercise the use of by-products as soil amendments according to the principles of TPP. Hence, the assessment of these substrates regarding their fertilizing effect and the evaluation of potential impacts on the local soil's nutrient budget was among the first tasks of the accompanied ecological research.

Substrates tested as soil amendment.

The following substrates derived from the CaSa- and BiogaST-projects were tested:

1. Urine collected in UDDT and stored for two months in closed jerry cans for sanitation.
2. Biogas slurry from the first pilot digester using banana tree stump mixed with cow dung for fermentation (mixture 1:1 by volume).
3. Grass is included in the assessment because, according to local practice, plots where biogas slurry is applied are covered with grasses.
4. Compost prepared by local farmers containing a mixture of fresh and dried grasses (91 vol%), ash (3 vol%) and kitchen waste (6 vol%). In addition, water was added to improve the moisture content of the mixture and topsoil was added to introduce microorganisms. Composting was done in one batch for about three months in a shallow pit in the ground, covered with soil and grasses to mitigate evaporation.
5. CaSa-compost containing sanitized human feces (15 vol%), biochar (17 vol%; residues from microgasification of eucalyptus-sawdust with pyrolitic temperature conditions of over 500°C, residence time ≥ 120 min), kitchen waste and harvest residues (15 vol%; beans straw, banana peels), mineral material (31 vol%; ash from three stone fire with eucalyptus wood, brick particles, local soil to add minerals and soil microorganisms) and woody material (22 vol%; sawdust, grasses). In addition, 1.2 dm^3 of stored urine was added per 10 dm^3 of solid material. Urine was mixed with sawdust or charcoal two days before addition to the compost pit so that N contained in urine could be adsorbed to the charcoal. Composting was done continuously with weekly addition of one pot of about 20 dm^3 of sanitized feces and the other materials in the respective amounts. The compost pit was located in a shallow hole under the shade of a tree and covered with grasses.

Analytical assessment of the soil amendments

A series of analyses were carried out to assess the fertilizing potential of the tested amendments. Total concentrations of nutrients, P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, Mn_{tot}, aluminium (Al_{tot}), and iron (Fe_{tot}), were determined after nitric acid (HNO_3) digestion under pressure using inductively coupled plasma optical emission spectrometry (ICP-OES; with iCAP 6000, Thermo Scientific, Waltham, USA) and method according to König (2005). Total concentrations of C (C_{tot}) and N (N_{tot}) were analyzed after dry combustion of oven-dry material using a thermal conductivity detector (with CNS-Analyzer, Vario ELIII, Elementar, Hanau, Germany) and method according to ISO DIN 10694 (1995) for C_{tot} and ISO DIN 13878 (1998) for N_{tot}. Mineral nitrogen (N_{min}) was extracted with potassium chloride (KCl) and analyzed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany). The method involved the suspension of 50 g material of the amenders in 0.1 dm^3 of 0.1 mol KCl. Within the same solution, pH was measured by using a glass electrode (pH 330i, WTW, Weilheim, Germany). In addition, gravimetric determination of water content of the fresh matter (wc_{FM}) was made for each material by weighing the materials before and after drying in a laboratory oven, at 105°C and 24 h for compost and at 65°C and 72 h for biogas slurry. Bulk density (ρ) of the composts was determined by filling 20 dm^3 buckets with equally poured fresh matter (FM) and measuring the weight respectively. Total concentrations of nutrients and C were measured at the laboratory of TU Berlin at the department of soil science. Other analyses were done on-site in MAVUNO's laboratory.

Data analyses

We calculated mean values (x) and standard deviations (σ) using MS Excel. For the experimental measurements, the numbers of replications (n) varied and were n=1, 2 and 5 for grasses, biogas slurry and compost as well as CaSa-compost respectively. We compared the assessed data considering the interval of x ± σ. Furthermore, we applied propagation of errors to determine the uncertainty of the calculated values.

RESULTS AND DISCUSSION

Nutrient concentrations in substrates derived from case studies

The pH of all tested substrates was similar and slightly alkaline (Table 1). According to literature, the pH of fresh urine depends on the nutrition and varies between 4.8 and 7.5. During storage the pH rises to 8.8 or 9.2 (Schönning and Stenström, 2004). The wc_{FM} ranged from 25.0 ± 13.1% to 33.6 ± 5.3 and 32.5 ± 1.9 up to 95.6 ± 0.5 % of the FM for grasses, compost, CaSa-compost and biogas slurry respectively. With 770.5 ± 8.9 g dm^{-3}, CaSa-compost had a higher bulk density of FM as compared to the local compost with 546.5 ± 1.5 g dm^{-3}. This might be related to the differences in content of C_{tot} in FM because CaSa-compost showed with 60.1 ± 6.9 g dm^3 nearly two times higher concentration than compost while concentration in biogas slurry was about half of that for CaSa-compost. With 5.3 ± 0.2 g kg^{-1} and 6.0 ± 0.5 g kg^{-1}, compost and CaSa-compost showed comparatively low N_{tot}, with a concentration of N_{tot} in DM typically around 12 g kg^{-1} for composts (Horn et al., 2010); compared to 19.9 ± 0.1 g kg^{-1} in biogas slurry. The dominant forms of available N_{min} were ammonium (NH_4^+) in biogas slurry and nitrate (NO_3^-) in compost and CaSa-compost, while the concentration was highest in biogas slurry and similar in both composts. Furthermore, CaSa-compost showed adequate fertilizing potential with concentrations of P_{tot} in DM of 3.2 ± 0.2 g kg^{-1}, compared to literature for composts made of organic residues with an average value of about 1 g kg^{-1} (Finck, 2007). With P_{tot} in FM of 1.7 ± 0.1 g dm^{-3}, the concentration was 3.6 times and 5 times higher compared to compost and biogas slurry respectively. In addition, concentrations of K_{tot}, Mg_{tot}, $Ca_{tot,}$ Zn_{tot} were higher in CaSa-compost compared to the other amendments.

Furthermore, the ratios of C and N, P, S need to be considered to avoid immobilization of N, P or S during organic decomposition after the application of the soil amendments. Thresholds are C/N > 25, C/P > 150

Table 1. Analytical assessment of the tested soil amendments.

	pH	wc	C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
	KCl	% (FM)	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}
Gras		25.0 ± 13.1	426.3	1.9	ua.	1.7	1.0	13.8	2.8	8.6	4.9	4.0	24.1	172.4
Biogas slurry	7.7	95.6 ± 0.5	347.8 ± 6.4	19.9 ± 0.1	16.0 ± 0.8	3.1 ± 0.02	7.6 ± 0.2	92.9 ± 8.4	12.2 ± 0.1	17.4 ± 0.9	4.0 ± 0.7	4.3 ± 0.07	115.3 ± 1.7	282.7 ± 8.8
Compost	7.4	33.6 ± 5.3	90.6 ± 7.7	5.3 ± 0.2	0.12 ± 0.04	1.2 ± 0.05	1.2 ± 0.1	8.5 ± 1.2	3.2 ± 0.2	10.0 ± 1.2	77.5 ± 1.6	65.2 ± 10.3	59.5 ± 4.3	641.4 ± 105.6
CaSa	7.5	32.5 ± 1.9	115.6 ± 11.4	6.0 ± 0.5	0.36 ± 0.07	1.3 ± 0.1	3.2 ± 0.2	14.6 ± 1.4	5.1 ± 0.5	29.6 ± 2.8	54.5 ± 1.4	83.5 ± 17.5	67.0 ± 4.7	480.2 ± 47.7
	ρ_{FM}	ρ_{DM}	C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	mg dm^{-3}	mg dm^{-3}
Gras	77.4 ± 0.7	58.0 ± 30.4	24.7 ± 13.0	0.1 ± 0.1	ua.	0.1 ± 0.1	0.1 ± 0.03	0.8 ± 0.4	0.2 ± 0.1	0.5 ± 0.3	0.3 ± 0.2	0.2 ± 0.1	1.4 ± 0.7	10.0 ± 5.2
Biogas slurry	1000 ± 50*	44.0 ± 2.2	15.3 ± 0.8	0.9 ± 0.04	0.7 ± 0.05	0.1 ± 0.01	0.3 ± 0.02	4.1 ± 0.4	0.5 ± 0.03	0.8 ± 0.1	0.2 ± 0.03	0.2 ± 0.01	5.1 ± 0.3	12.4 ± 0.7
Compost	546.5 ± 1.5	362.9 ± 57.2	32.9 ± 5.9	1.9 ± 0.3	0.04 ± 0.02	0.4 ± 0.1	0.5 ± 0.1	3.1 ± 0.7	1.1 ± 0.2	3.6 ± 0.7	28.1 ± 4.5	23.7 ± 5.3	21.6 ± 3.7	232.8 ± 53.1
CaSa	770.5 ± 8.9	520.1 ± 31.0	60.1 ± 6.9	3.1 ± 0.3	0.2 ± 0.04	0.7 ± 0.1	1.7 ± 0.1	7.6 ± 0.9	2.7 ± 0.3	15.4 ± 1.7	28.3 ± 1.8	43.4 ± 9.5	34.9 ± 3.2	249.7 ± 28.9
Urine **	1030	30	8.0	9.2	n.a.	1.5	0.5	2.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Element concentrations in DM of the tested soil amendments [g kg^{-1} and mg kg^{-1}] and bulk density of FM (ρ_{FM}) [g dm^{-3}] were analyzed and are displayed with mean value and standard deviation with n=1, 2 and 5 for grasses, biogas slurry and compost as well as CaSa-compost respectively. Element concentrations in FM based on volume [g dm^{-3} and mg dm^{-3}] and bulk density of DM (ρ_{DM}) [g dm^{-3}] are calculated by using wc and displayed with mean values and standard error calculated applying propagation of error. *Density of slurry was unanalyzed (ua.); assumption is based on literature for liquid biogas slurry (Vögeli et al., 2014). ** Values are based on literature for stored urine (Berger, 2008; some concentrations were not available, n.a.)

and C/S > 150 (Finck, 2007). With C/N of about 18, 17 and 14for biogas slurry, compost and CaSa-compost respectively, the immobilization of N is not likely. The same was shown for the immobilization of P with C/P ratios of 46, 73 and 36 and immobilization of S with C/S ratios of 114, 74, 63 for biogas slurry, compost and CaSa-compost respectively. Compared to the assessed amendments, N_{tot}-concentration in urine is comparatively high and concentration of P_{tot} and K_{tot} are in the range of compost with 0.5 and 2.2 g dm^{-3} respectively (Berger, 2008). However, according to Finck (2007), plants will initially utilize only a certain proportion of the added nutrients of the assessed fertilizing amendments. The remaining amount will stay in the soil and be taken in the next cropping seasons, if not leached out (e.g. for S, N), volatilized (e.g. for N) or taken away through erosion (e.g. for P). Hence, the total concentrations we presented here should be considered as “apparent” utilizations (Finck, 2007) or specific nutrient recycling potential.

Assessment of the tested amendments with respect to nutrient availability in the soil

The availability of nutrients in the soil is, among other factors, a function of soil pH. The optimum range of pH for agricultural soils depends on the clay content as well as on the concentration of SOM and is, on an average, between 5.5 and 6.5 (Horn et al., 2010; Finck, 2007). An increase of soil pH in the topsoil, depending on the treatment and the respective nutrient addition, has often been considered to have an immediate impact on harvest yield (Jeffery et al., 2011; Liu et al., 2013). Falcão et al. (2009) argued that the high productivity of plants growing on Terra Preta is inter alia due to the improved pH and consequent reduction of Al-toxicity.

As mentioned earlier, in preliminary studies we found very low values of about 3.8 to 4.2 for soil pH in Karagwe. Commonly, lime ($CaCO_3$) is used to neutralize soil acidity (Horn et al., 2010). However, organic material also has the potential to buffer acids in soils (Wong et al., 1998). Furthermore, Biederman and Harpole (2013) concluded that the addition of biochar can improve the availability of nutrients in the soil through soil liming effects.

Table 2. Effects on soil acidification or alkalization of the tested soil amendments in comparison to organic (Jobe et al., 2007) and synthetic fertilizers (Sluijsmansen, 1970; KTBL, 2009; Fink, 1979) expressed in kg of CaO in 100 kg of DM and in kg of CaO in each kg of N_{tot}.

Treatment	E	
	kg_{CaO} 100 kg_{DM}^{-1}	kg_{CaO} kg_{N}^{-1}
Tested soil amendments		
Biogas slurry	+ 6.8	+ 3.4
Compost	+ 1.4	+ 2.6
CaSa-compost	+ 4.7	+ 7.8
Organic fertilizers		
Poultry manure I	+ 14	+ 10.0
Fish waste I	+ 3.5	+ 0.8
Fish waste II	+ 3.5	+ 0.8
Poultry manure II	+ 13.6	+ 9.7
Sugar molasses	+ 3.5	+ 1.4
Cattle manure	+ 2.7	+ 2.1
Synthetic fertilizers		
Ammonium sulfate	- 63	- 3
Calcium ammonium nitrate (22% N)	- 4	0
Urea	- 46	- 1
Calcium nitrate	+ 13	+ 1

Wong et al. (1998) proposed an acid titration method to quantify the acid neutralizing capacity of compost (ANC). Jobe et al. (2007) used this method and estimated ANC ranging between 95 and 500 cmol H^+ kg^{-1} for six different composts. If complete mineralization of the compost and oxidation of organic N and S are considered, which is reasonable under tropical soil conditions, the ANC may, however, simply be calculated as the difference between metal- (M+) and non-metal-equivalents (A-) in the compost. This is possible, because the mineralization of M+ is a H^+-sink and the mineralization of A- is a H^+-source (Van Breemen et al., 1983). Under these conditions the formula which was developed by Sluijsmans (1970) for the prediction of the liming effect E, expressed as kg CaO equivalent of 100 kg of DM of any fertilizer may be applied:

$$E = (1.0 \times CaO + 1.4 \times MgO + 0.6 \times K_2O) - (0.4 \times P_2O_5 + 0.7 \times SO_3 + 2 \times N) \quad (1)$$

The amounts of nutrients (CaO, MgO etc.) are to be inserted into the equation in kg of nutrient per 100 kg of fertilizer. Overall, the compost application will cause acidification if $E < 0$ and alkalization if $E > 0$.

The results of our calculation using Equation 1 are presented in Table 2 and compared with literature for selected organic and synthetic fertilizers (Sluijsmansen, 1970; KTBL, 2009; Fink, 1979; Jobe et al., 2007). In addition, we calculated the liming effect related to N in the various fertilizers.

Additions of 100 kg of DM of, respectively, biogas slurry, compost or CaSa-compost are equivalent to 6.8, 1.4 and 4.7 kg of CaO. Thus, all products will cause alkalization and reduce acidity of the soil. Our results are well in line with the range of pH buffering capacity of different composts given by Jobe et al. (2007). The liming effect related to N_{tot} in the tested amendments is similar for biogas slurry and compost, with 3.4 and 2.6 kg of CaO per kg of N_{tot} respectively, while the value is more than doubled for CaSa-compost. In comparison with our results, most synthetic N-fertilizers that are commonly used would cause soil acidification. For example, if 100 kg of urea are applied as N_2-fertilizer, about 46 kg CaO are needed to buffer the acidification effect in the soil. Among the synthetic N-fertilizers only calcium nitrate ($Ca(NO_3)_2$) has a positive value for E with 100 kg of calcium nitrate being the equivalent of 13 kg of CaO and 1 kg N addition being the equivalent of 1 kg CaO.

Since Batjes and Sombroek (1997) pointed out that “stable increase in SOM in deeply weathered tropical soils occur especially with addition of phosphate and lime”, we deduce that all of the assessed soil amendments can contribute to sustainable soil improvement through P-recycling and liming with this holding true especially for CaSa-compost. Increased P-levels in the soil may also contribute to mitigation measures since crops may root deeper and, thus, are less vulnerable to droughts and render P-cycling through organic residues more effective (Batjes and Sombroek,

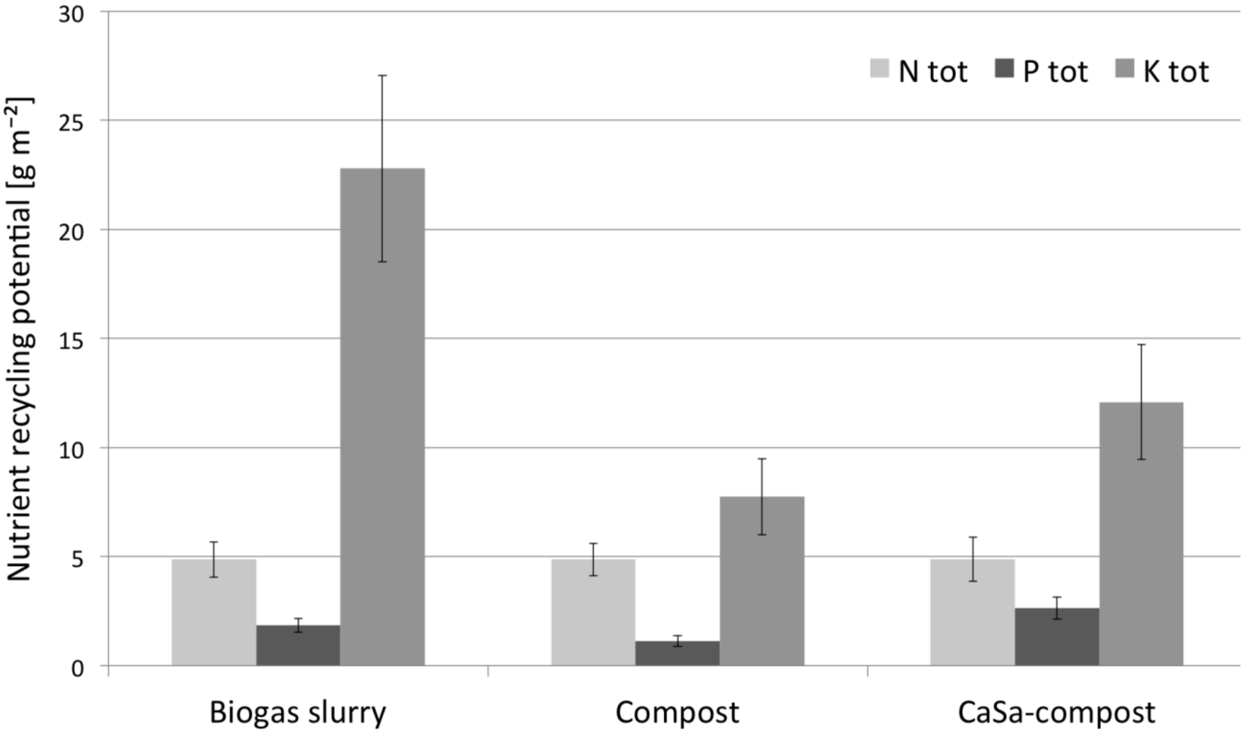

Figure 3. Total nutrient recycling potential expressed in nutrient addition [g m^{-2}] for N_{tot}, P_{tot}, and K_{tot} corresponding with application doses of 5.5, 2.5 and 1.6 dm^3 m^{-2} for biogas slurry, compost and CaSa-compost respectively.

1997).

Estimation of the total nutrient recycling potential in agricultural practice

According to Mafongoya et al. (2007), the amount of manure applied by farmers in SSA is on an average within a range of 1 to 1.5 kg m^{-2} per year which is equivalent to about 1.8 to 2.7 dm^3 m^{-2} (calculated with ρ_{FM} as presented in Table 1). Hence, we estimated the total nutrient recycling potentials for N_{tot}, P_{tot} and K_{tot} in g m^{-2} in the tested soil amendments (Figure 3).

An application of the tested local compost in FM with 2.5 dm^3 m^{-2} per year resulted in a potential nutrient addition to the soil of 4.9 ± 0.8, 1.1 ± 0.3 and 7.7 ± 1.8 g m^{-2} a^{-1} for N_{tot}, P_{tot} and K_{tot} respectively. According to the premise, that the same dose of N should be obtained with the other tested soil amendments, we subsequently calculated the necessary application of CaSa-compost and biogas slurry in FM to be 1.6 ± 0.3 and 5.5 ± 0.9 dm^3 m^{-2} a^{-1} respectively. Thus, to reach the same level of N-application, the required amount of CaSa-compost is, on average, only about 65% of the required amount of conventional compost. In other words, an available amount of 1000 dm^3 of compost material in FM would suffice for application on 400 m^2 by using compost and on about 630 m^2 by using CaSa-compost. Given these specific application doses, the resulting addition of P_{tot} by CaSa-compost would be about 1.4 and 2.3 times higher compared to biogas slurry and compost respectively. Ranging from 1.1 up to 2.6 g m^{-2} a^{-1} the estimated recycling potentials for P_{tot} are very low, especially on soils with low P-concentrations (KTBL, 2009; Finck, 2007). The calculated recycling potential for K_{tot} is about 7.7 g m^{-2} for compost and 1.6 and 2.9 times higher for CaSa-compost and biogas slurry respectively. With the estimated K-additions, the local compost as well as CaSa-compost meet the requirements for appropriate K-fertilization on soils, with an adequate K-supply of about 13 to 19 g m^{-2} on an average (KTBL, 2009; Finck, 2007). Only biogas slurry exceeds this fertilizing recommendation. According to Finck (2007), an increasing addition of K lowers the uptake of Ca and Mg during plant growth (“antagonism of nutrient uptake”). Given the K-addition with biogas slurry, it is recommendable to mix (or compost) biogas slurry prior to its application with other materials containing more N and P compared to K to reach a better balanced nutrient ratio of N:P:K. This ratio was 4:1:7, 2:1:5 and 3:1:12 for compost, CaSa-compost and biogas slurry respectively. Furthermore, the corresponding input of C_{tot} would be about the same for all tested soil amendments with 86 ± 14, 82 ± 15 and 96 ± 21 g m^{-2} for biogas slurry, compost and CaSa-compost respectively. However, the kind of C differed in the materials, as CaSa-compost contains biochar, that is, a source of stable C.

Estimation of the local potential to close the loop

Stoorvogel et al. (1993) calculated soil nutrient balances for African countries for the year 2000. They considered mineral fertilizer, animal manure, dry deposition, biological N-fixation and sedimentation as inputs to the agricultural land, while the removal of harvest products and crop residues, leaching, gaseous emissions and erosion were accounted for as losses. Their results showed an average negative balance per year and per square meter of 3.2 g N, 0.5 g P, and 2.1 g K on arable land in Tanzania. Looking at a neighboring country, bordering Kagera region, Jönsson et al. (2004) assessed that the human excreta of one Ugandan person contains in total 2.5 kg N and 0.4 kg P per year. Combining this data, we estimated the recycling potential of EcoSan for one family with 6 people to be about 15 kg N and 2.4 kg P per year, which would be sufficient to cover the negative balance of approximately 4800 m^2. Furthermore, Baijukya and de Steenhuijsen Piters (1998) calculated "Nutrient balances in the banana-based land use systems of northwest Tanzania", including Karagwe district. In addition to the balances of Stoorvogel et al. (1993), they also considered mulching and subsoil exploitation by perennial trees as input flows. Their balances were done for farms with different nutrient management levels. For farms without cattle and without brewing activities (lowest management level), they calculated an average loss per year of around 2.8 g N, 0.3 g P, and 3.0 g K on one m^2. They concluded that "substantial amounts of nutrients are lost through human feces and end up in deep pit latrines" and demanded changes in the sanitation system to "facilitate the recycling of nutrients in feces" (*ibid*.). On this basis, we assessed the potentials of the tested soil amendments to contribute to the local nutrient budget to close the loop. As P-scarcity was identified as a major problem in our pre-studies and since N-fertilization can more easily be realized with the use of urine as a fertilizer, we calculated the required amounts for compensation of the negative P-balance.

Our results show that the estimated required amount of FM is approximately 6 and 3 times higher for biogas slurry and compost respectively as compared to CaSa-compost with about 0.1 kg m^{-2} a^{-1} (Figure 4). Respective amounts based on volume are considered feasible, ranging from around 0.2 to 0.8 dm^3 m^{-2} a^{-1}. Given the fact, that one farmer household in Karagwe cultivates on average 6,225 m^2 (Tanzania, 2012), the required total amounts of FM per household to close the loop for P would be 5.0, 2.0 and 0.8 t a^{-1} for biogas slurry, local compost and CaSa-compost respectively. However, by adding the respective substrates to the soil, negative balances for N and K still remain. Considering calculated amounts and N_{tot}-concentration of the substrates, we calculated that the N-deficit would be covered by 26, 42 and 18% for biogas slurry, compost and CaSa-compost respectively. Additional nutrient requirements could be covered, for example, by applying urine as fertilizer with about 0.2 dm^3 m^{-2} a^{-1} according to own calculations. Hence, the total amount of urine required to cover the remaining N-deficit on one small-scale farm in Karagwe with 6,225 m^2 cultivated land would be about 1.7, 1.3 and 1.8 m^3 a^{-1}. According to Winblad et al. (2004) the excreta of person includes 1 dm^3 urine per day so that one family with 6 people has about 2.2 m^3 urine available per year and could finally close the local nutrient balance on their farmland.

CONCLUSION AND RECOMMENDATION

The introduced projects and case studies of this research present an integrated approach of resource management where different substrates rich in mineral nutrients, such as ash, biogas slurry, stored urine and sanitized feces are recycled in combination with C-rich materials such as biochar. The results of our first investigations support our hypothesis that new approaches that combine EcoSan, bioenergy and TPP can contribute to the recycling of nutrients and C-sequestration as well as to soil improvement. The analytical assessment of the substrates derived from these projects showed that all of the tested substrates are feasible soil amendments due to their sufficient nutrient concentrations and adequate nutrient ratios compared to literature. Based on the more practice-oriented volume [dm^3], CaSa-compost showed the highest concentration of all nutrients as well as C, followed by compost and biogas slurry. Furthermore, all tested soil amendments have good liming potential compared to other soil amendments. As $CaCO_3$ is usually quite expensive, we conclude that all tested substrates are a feasible low-cost option for liming. Especially the locally produced CaSa-compost is promising due to the comparatively high P-concentration and E-value for liming. Under the circumstances given in Karagwe, sufficient application rates of CaSa-compost can contribute to mitigating existing P-scarcity and acidification in the soil and, consequently, to increasing biomass production. Furthermore, our final evaluation revealed that amounts of FM of less than one dm^3 m^{-2} a^{-1} of the assessed materials in combination with urine are required to close existing open nutrient cycles (for P and N) in Karagwe. However, higher amounts of the soil amendments are required if they should be applied as a major source of nutrients, in order to provide a full substitution of the existing input of mineral fertilizer and animal manure. We conclude that EcoSan combined with TPP as well as the use of biogas slurry are promising practices to close the loop in the agroecosystems in SSA (as well as elsewhere). However, there is a need for practice-oriented experiments to assess short and long-term effects of these amendments on biomass production

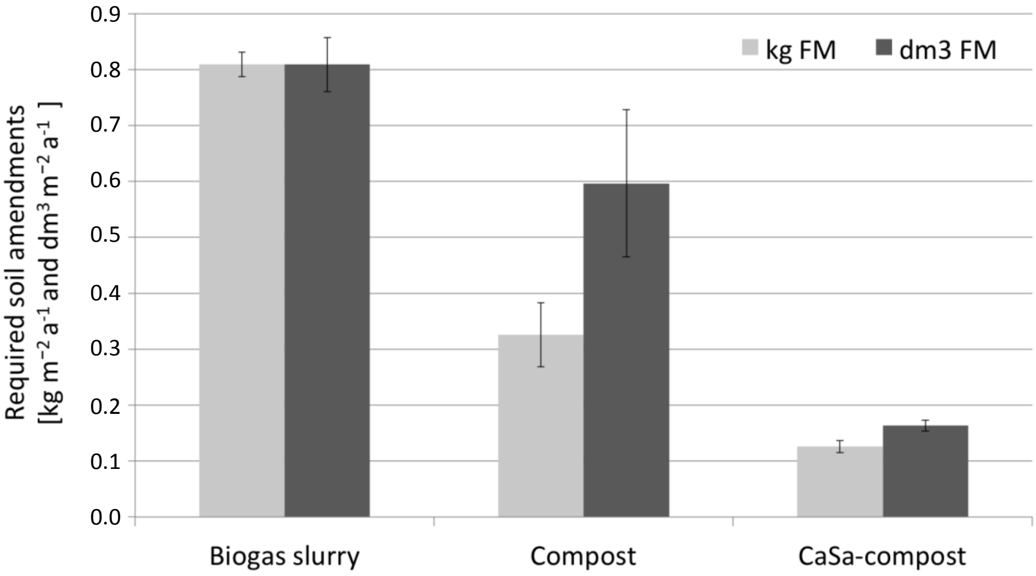

Figure 4. Calculated required amounts of FM of the tested substrates [kg ha^{-1} a^{-1} and dm^3 ha^{-1} a^{-1}] to compensate the negative P-balance of 0.3 g m^{-2} a^{-1} in banana-based land use systems of northwest Tanzania (Baijukya and de Steenhuijsen Piters, 1998).

and soil properties. Altogether, the strategies to investigate further potentials of the substrates derived from the projects include (1) practice-oriented field experiments to compare and to assess the short-term effectiveness of urine, biogas slurry, compost and CaSa-compost as a fertilizer with respect to crop productivity and crop nutrition as well as potential soil improvements. Furthermore, the applied resource management approach, as it is practiced in the introduced projects, should be (2) integrated in the local nutrient and C balance by using methods such as Material Flow Analysis and (3) should finally be evaluated including other perspectives than only the ecological one (e.g. socio-economic) by using Multi-Criteria Analysis. In addition, long-term field experiments are required to investigate the sustainable effects on SOM and other fertility-related soil parameters, such as the water holding capacity.

Conflict of Interests

The authors have not declared any conflict of interests. All partner organizations of the projects agreed to the ecological research on the projects and that the products will be assessed and that the results will be published.

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Abbreviations

Biochar, Charcoal used as soil amendment; **BiogaST,** Project “Biogas Support for Tanzania”; **CaSa,** Project “Carbonization and Sanitation”; **CaSa-compost,** Product of CaSa-project containing composted biochar and sanitized excreta; **CHEMA,** Community Habitat Environmental Management; **CREEC,** Center for Research in Energy and Energy Conservation; **EcoSan,** ecological sanitation; **EfCoiTa,** Project “Efficient Cooking in Tanzania”; **EWB,** Engineers Without Borders; **IAASTD,** International Assessment of Agricultural Knowledge, Science and Technology for Development; **ICP-OES,** Inductively coupled plasma optical emission spectrometry; **IGZ,** Leibniz Institute of Vegetable and Ornamental Crops; **MAVUNO,** MAVUNO Project Improvement for Community Relief and Services;

(“mavuno” meaning “harvest” in Swahili); **m.a.s.l.,** meter above sea level; **SOM,** soil organic matter; **SSA,** Sub-Saharan Africa; **TLUD,** top-lit up draft; **TPP,**Terra Preta practice; **TU,** Technische Universität; **UDDT,** urine diverting dry toilet; **WHO,** World Health Organization.

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