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Potential Economic and Environmental Benefits of Faecal Sludge Derived Compost and Char Briquettes: The case of Dar es Salaam, Tanzania

Isabela T Mkude[1*], Richard Kimwaga[1] and Sara Gabrielsson[2]
[1]*Department of Water Resources Engineering, College of Engineering and Technology, University of Dar es Salaam, P.O. Box 16103 Dar es Salaam, Tanzania.*
[2]*Lund University Centre for Sustainability Studies, Lund University, Box 170, SE-221 00 Lund, Sweden.*
**Corresponding author, e-mail: isabela.thomas@yahoo.com*
Co-authors' e-mails: rkimwaga2007@yahoo.com, Sara.gabrielsson@lucsus.lu.se
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Abstract

The concept of resource recovery, particularly from waste has recently gained much attention and popularity. The aim of this study was to quantify the potential economic and environmental benefits of recovering nutrients and energy from faecal sludge (FS). The empirical data were collected from three unplanned settlements of Dar es Salaam City at Keko, Kipawa and Manzese. Two scenarios were developed to recover nutrients and energy. The estimations of potential amounts of compost and char briquettes were performed by using the resource value mapping (REVAMP) tool. Results from REVAMP indicated daily economic benefits across the study areas ranging between 680 and 950 USD for energy and up to 7,000 USD for nutrients recovered, based on the faecal sludge composition. In general, FS derived compost was found more profitable than FS derived briquettes. The analyzed environmental benefits include saving the estimated to 5 hectares of forest area from being cut when substituting the use of wood charcoal with FS-derived briquettes. Since the composting process resulted to be more profitable option between the two, this study recommends the adoption and scaling up. However, guidelines and standards should be developed for proper practices.

Keywords: Faecal sludge; resource recovery; resource value mapping; briquettes; compost; economic benefits; environmental benefits.

Introduction

In the world of scarce resources, several alternatives have been explored to meet the growing demands (Esrey et al. 2001, Chianu and Chianu 2012, Mwampamba 2017). Resource recovery and reuse (RRR) from waste is one among alternatives under considerations. In sanitation management, RRR is a new dimension that focuses to optimize resource use in connection to water, energy and food systems (Esrey et al. 2001). The linear waste management solutions focus on treatments that aim for disposal, the RRR concept on the other hand is in a circular manner, closing the sanitation loop by turning human waste into a valuable resource (Rao and Otoo 2017). In Dar es Salaam, Tanzania, more than 90% of the population depend on onsite sanitation systems including pit latrines and septic tanks, while only about 43% of the collected faecal sludge (FS) is safely managed (Brandes et al. 2015). However, a piled-up semi-solid FS after partial treatment in waste stabilization ponds (WSPs) needs proper and adequate management to ensure safe disposal without posing any environment and human health risks (Gold et al. 2014). Various options for sustainable Faecal Sludge Management (FSM) have been developed for safely and sustainably recovering of FS resources to be used as plant nutrients, water for irrigation, energy, and for production of protein for animal feeds (Diener et al. 2014, Ddiba 2016, Strande et al. 2018).

One of the major environmental benefits from increased FS-RRR is reducing and averting nutrient loads causing eutrophication due to disposal of FS into water bodies (Harder et al. 2019). Resource recovery technologies also when mainstreamed in FSM strategies, have the potential to contribute into achieving several sustainable development goals (SDGs) such as improving soil fertility and animal feed options to ensure food security and to provide renewable energy sources to contribute to energy security (Diener et al. 2014).

Even though several products can be obtained from RRR, it is known that potential market values of the same end-products vary significantly in different countries where FS-RRR has been practiced (Harder et al. 2019). To ensure the most viable and sustainable end-product, it is therefore important to assess economic and environmental values of the anticipated end-product beyond the FS amount (Diener et al. 2014).

While the practice of FS-RRR in Dar es Salaam is still at infancy stage, lacking information on economic and environmental benefits of produced FS-derived products, therefore research on the potential and possibilities of FS-RRR has begun. In a study by Mkude et al. (2019), the FS characteristics and available volume were estimated to determine the resource recovery potential from OSSs in three unplanned settlements of Dar es Salaam. Advancing from the same information, the objective of this article is to assess the potential economic and environmental benefits of future FS-derived products using the Resource Value Mapping (REVAMP) tool developed by the Sustainable Sanitation Initiative at the Stockholm Environment Institute (SEI 2016).

The resource value mapping (REVAMP) is a tool developed as a Microsoft Excel spreadsheet with built-in formulae that consist of six (6) working sheets. The tool was developed for rapid estimation, valuation and visualization of the potential resources to be recovered from organic waste streams in urban areas. REVAMP includes sewage sludge, faecal sludge, as well as food and other organic solid waste (SEI 2016). The current available recovery technologies for evaluation in REVAMP tool are biogas production, solid fuel for combustion, insect larvae for livestock feeds, and compost or soil conditioner materials for agriculture (Ddiba 2016).

Methodology

Study design

The study employed a cross-sectional research design combining both qualitative and quantitative methods of data collection including household surveys, observations, key informant interviews and focus group discussions with the key stakeholders involved in FSM in Dar es Salaam.

Description of the study sites

The study was conducted in three unplanned settlements in Dar es Salaam City, namely Keko, Kipawa and Manzese, located in Temeke, Ilala and Ubungo Municipality, respectively. The areas are densely populated, estimated to have 224,140 people in total occupied in 19 km^2 area with average household occupancy of 6 people (URT 2017). The areas were considered due to their similarities, almost all the population (99.2%) depending on onsite sanitation systems both pit latrines and septic tanks for their sanitation services and needs (Mkude et al. 2019). The reported average per capita water use is still low, approximately to 22.4 ± 9.1 l/cap/d for bathing and 46.5 ± 27.9 l/cap/d for other purposes.

Study approach

Resource recovery scenarios analysis

Zero or baseline scenario

The status quo of FSM in Dar es Salaam does not consider resource recovery. The same situation was used to present amounts of FS and nutrients contained from collection to disposal.

Scenarios for a change

Two scenarios represent hypothetical future recovery plans in Dar es Salaam were developed in this article including energy recovery (*EnRec*) via production of FS-derived briquettes to be used as domestic cooking fuel and nutrient recovery (*NutRec*) via compost production to be used as organic fertilizer in agriculture (see Figure 1).

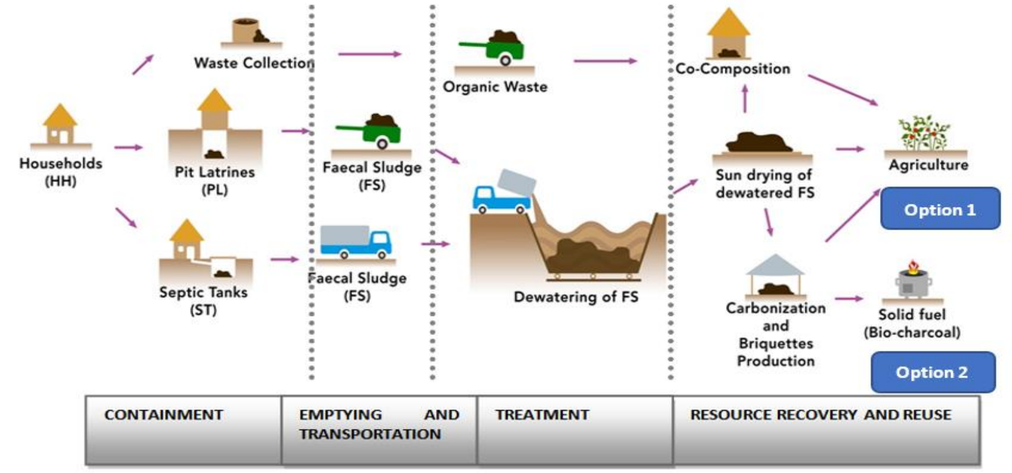

Figure 1: Schematic presentation of proposed resource recovery scenarios; Option 1: Co-composting and Option 2: Solid fuel production.

The *EnRec* scenario analyzes the possible uses of dewatered faecal sludge to produce solid fuel as an alternative cooking fuel through carbonization process to obtain char material, then compaction with water and binding materials. Addition of bulking materials is suggested for the purpose of increasing fuel energy contents (Lohri et al. 2015).

The *NutRec* scenario considers the possible use of composted FS as an alternative or supplement to organic fertilizers and other animal wastes currently applied by local farmers to improve soil fertility (Benson et al. 2012). To obtain a higher nutrient content level and to obtain the suitable carbon to nitrogen balance, FS has to be co-composted with organic wastes such as food wastes or other municipal solid waste fractions (Esrey et al. 2001).

Data collection method

Data collection took place between September 2017 and November 2018 using the mixed method of data collection including literature review, household survey, key informants' interview and focus group discussions. A total of 395 respondents participated in the household surveys, interviewed 19 key informants, and six focus group discussions were conducted in the study areas. The amounts of FS generated together with nutrients (nitrogen and phosphorus) contained in FS and transported along the sanitation service chain were analyzed by using the Material Flow Analysis (MFA) technique as reported by Mkude et al. (2019).

Steps followed in the application of REVAMP analysis

In the first step, the data input sheet was filled for each study area individually per each resource recovery scenario; composting and solid fuel production. Market price of each end-product was identified from the literature review and from key informants' interviews in comparison to the alternative products in the market. Table 1 presents input information identified from the estimated FS amount and fractions previously analyzed by material flow analysis and reported by Mkude et al. (2019).

Table 1: The general information used to estimate input data in developed scenarios

	Study location			
	Keko	Kipawa	Manzese	Reference
Population	79,453	74,180	70,507	URT 2017
Fraction of pit latrines out of OSSs, %	27.1	35.9	61.8	
Fraction of septic tanks out of OSSs, %	72.1	63.4	38.2	
Volume of FS delivered to treatment plants (l/ca/yr)	408.80	434.35	646.05	Mkude et al. 2019
Nitrogen (tons/yr)	293.91	318.70	359.48	
Phosphorus (tons/yr)	29.95	23.03	28.59	
N (mg-N/l)	9,048.80	9,891.30	7,891.81	This study
P (mg-P/l)	922.1	714.77	627.65	This study

Data analysis using the REVAMP tool

Data analysis for each recovery option was conducted by REVAMP tool based on eight (8) equations accordingly as expressed by Ddiba (2016).

Potential amount of FS-derived briquettes

The estimations of FS-derived briquettes quantity were given as products mass (B_m) (tonnes) and as calorific value (CV) or energy content (MJ/kg TS) using Equations 1 and 2.

$$B_m(tonnes) = FS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100}{90} \quad (1)$$

$$E_F(MJ) = FS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100}{90} \times CV \quad (2)$$

Where; FS_v is the volume of collected FS, TS_v is the volume of total solids in mg/l, E_F is the energy content of a fuel in MJ (Diener et al. 2014).

The revenue from sales was calculated based on a mass of briquettes in tonnes (B_m) and the price (F_p) in US$/tonne as shown in Equation 3.

Potential revenue from briquettes =

$$B_m(tonnes) \times F_p(US\$/tonne) \quad (3)$$

Input data for EnRec scenario

Table 2 summarizes input data used for *EnRec* scenario calculations mostly obtained from the literature.

Table 2: Input data to REVAMP tool specific for *EnRec* scenario

S/N	Item	Value adopted and used	Reference
1.	Faecal sludge total solids (TS)	30,000 mg/l	Schoebitz et al. 2014
2.	Faecal sludge calorific value of dried FS at 90% dryness	16.2 MJ/kg	Diener et al. 2014
3.	Cost of charcoal	0.60 US$/kg	Msuya et al. 2011
4.	Cost of biomass briquettes	0.26 US$/kg	Lohri et al. 2015

Potential amount of FS-derived compost

To achieve a complete composting process, FS with 60% dryness is recommended while mass reduction of combined waste is expected to occur (Ddiba 2016). The amount of compost, C_m (in tonnes) that can be obtained at 60% dryness, was calculated using Equation 4.

$$C_m(tonnes) = FS_v \times 1000 \times \frac{TS_v}{10^9} \times \frac{100-\mathrm{CMR}}{100} \times \frac{100}{60} \quad (4)$$

The revenue from compost sales was calculated based on the mass of compost (C_m) and the price of compost fertilizer (C_p) according to Equation 5.

Potential revenue from compost =

$$C_m(tonnes) \times C_p(US\$/tonne) \quad (5)$$

Nutrient's reduction (NR_C) is normally expected through composting. Therefore, the expected nutrient content NUT_C (tonnes) for nitrogen and phosphorus in compost were calculated for both FS and organic MSW separately using Equation 6 and Equation 7, respectively and in percentages according to Equation 8.

$$NUT_C(tonnes) = FS_v \times 1000 \times \frac{NUT_v}{10^9} \times \frac{100-\mathrm{NR}_C}{100} \quad (6)$$

$$NUT_C(tonnes) = OW_w \times \frac{\mathrm{TS}_m}{100} \times \frac{NUT_w}{10^6} \times \frac{100-\mathrm{NR}_C}{100} \quad (7)$$

Where; $\mathrm{NUT_C}$ expresses the nutrient content, either nitrogen or phosphorus, and $\mathrm{OW_w}$ is the weight of organic waste.

Nutrient content in the compost (%) =

$$\frac{NUT_C\ (tonnes)}{C_m(tonnes)} \times 100 \quad (8)$$

Input data for NutRec scenario

Table 3 presents a summary of input data specific for *NutRec* scenario calculations as applied to the REVAMP tool.

Table 3: Input data to REVAMP tool specific for *NutRec* scenario analysis

S/N	Item	Available	Reference
1.	Organic waste (78% of total waste generation)	0.09-3.0 kg/ca/d	Kirama and Mayo 2016
2.	Price of packaged compost	0.43 US$/kg	Local NGO Interview, 2018
3.	Total nitrogen reduction from FS during composting, ($\mathrm{NR_{N\text{-}FS}}$)	34.3% of the initial mass	Schoebitz et al. 2014
4.	Total nitrogen reduction from OW during composting, ($\mathrm{NR_{N\text{-}OW}}$)	50% of the initial mass	Esrey et al. 2001
5.	Total phosphorus reduction during composting, ($\mathrm{NR_P}$)	1.8% of the initial mass	Schoebitz et al. 2014
6.	Dry mass reduction in compost	19.4% of the initial mass	Schoebitz et al. 2014

Economic benefits indicators of FS resource recovery

The economic values of FS derived products were determined in two ways. First, the revenues calculated from potential direct sales and the second value was obtained as potential saved costs from desludging, transport, treatment and disposal of FS as calculated by modified Equation 9 from Rangga et al. (2019).

TC = ∑ [(FS volume, (m^3/yr) × desludged frequency, (month/year) × Desludging fee, (USD /m^3)) + (FS volume disposed, (m^3/yr) × Disposal fee, (USD /m^3))] (9)

where, TC = total cost saved, FS = Feacal sludge and USD = United States Dollar

The market value price was used to estimate the economic value with an exchange rate of 1 US$ = 2,277 Tshs obtained on 15th November, 2019 (www.bot.go.tz).

Environmental benefits indicators from resource recovery implementation

Environmental benefits from applying RRR was analyzed as estimated forest area saved from wood charcoal production by substituting wood charcoal with FS derived fuel (Mwampamba 2017) as:

Forest area (hectares) = $(\mathrm{M_s} \times \mathrm{E_k})/S$ (Eq. 10)

where; $\mathrm{M_s}$ is the mass of single sack (kg of charcoal/sack), $\mathrm{E_k}$ is charcoal kiln efficiency (tones of wood/tones of charcoal) and S is the stock density (tonnes of wood/hectare of the forest).

In this case, a common single sack of charcoal packaged was taken as 50 kg and a traditional unimproved earth kilns with 10% efficiency commonly used in Tanzania (Msuya et al. 2011). The average stock density is 66 t/h. However, not all 100% of the forest is harvested for wood charcoal, hence 93% of stock density is suggested for calculation purposes (Mwampamba 2017). Using the formula expressed (Eq.10) with adopted parameters, the forest area needed to produce 1 tonne of charcoal is 0.00162 ha.

Results and Discussion

Nutrients and energy contents in FS from study areas

Based on the estimated amount of FS collected and delivered to treatment plants from each study area, the daily potential nutrients and energy content was also estimated per study area as presented in a combined bar and scatter plot chart (Figure 2).

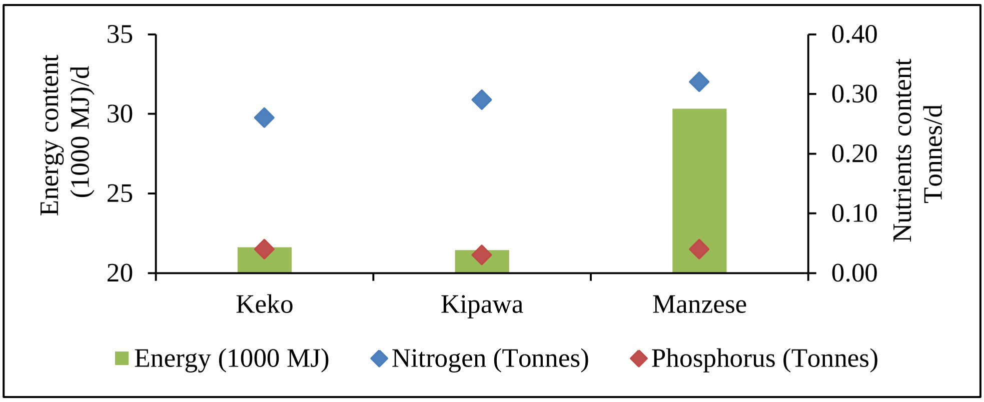

Figure 2: Nitrogen, phosphorus and energy content estimated from the available daily amount of FS.

The content of nutrients shows the largest amount of nitrogen was obtained from Manzese area, about 29% more than Keko and Kipawa. This could be explained by the fact that Manzese is predominantly served by large portion of pit latrines. Pit latrines contain undiluted faecal sludge which is relatively slowly digested as compared to septic tanks (Strande et al. 2018). In addition, the accumulation and dispersion mechanisms which determine the nitrogen and phosphorus concentrations are slow in pit latrines as compared to septic tanks (Montangero 2006). Similarly, the energy value from raw FS varied with location, with the highest amount coming from Manzese, again, likely linked to the undigested nature of FS found in pit latrines.

Analysis of resource recovery scenarios

Potential amount of composted FS and solid fuel generated

The co-composting process involved the mixing of FS and organic waste (OW) mixture. As expected, the largest amount of co-compost product comes from the most populated area, Keko; since the amount of organic waste was calculated based on generation rate per capita. Here, a possible total daily amount of 49.9 tonnes of faecal sludge derived compost could be produced across study areas as shown in Figure 3.

The total annual amount of solid fuel generated across the study areas are 3,310.55 tonnes equivalent to daily production of 9.07 tonnes. The lower amount of solid fuel compared to the composted FS was probably attributable to the pyrolysis process which reduces the initial weight of dried FS up to 50% or more (Lohri et al. 2015). Another possible reason is that, in the briquettes production analysis, no added feedstock materials used for co-firing or binding materials other than FS as it was for the case of composting which could also enhance the mass addition of the final product obtained.

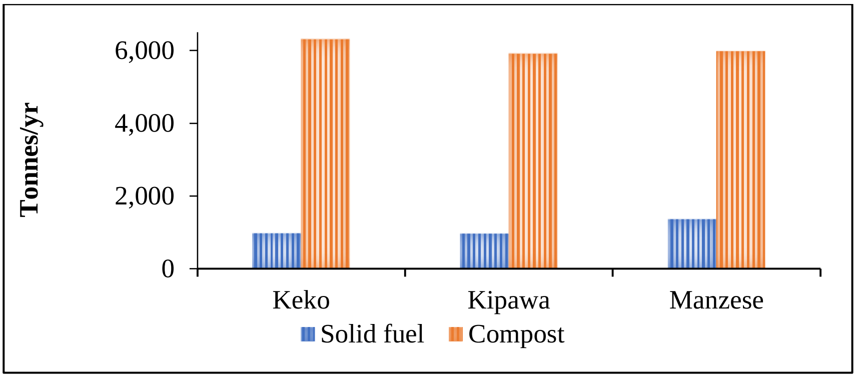

Figure 3: Amount of compost and solid fuel produced per year in the study area.

Generally, the findings show high availability of nutrients (nitrogen and phosphorus) contents from raw FS which can be recovered for agricultural purposes. About 0.26–0.32 tonnes of nitrogen and up to 0.04 tonnes of phosphorus contents in raw FS could be recovered annually. The main source of phosphorus content in OSSs is reported to be contributed by soaps and detergents used in cleaning and personal health care products (Harder et al. 2019). This might be similar to this case as majority of houses in this study were observed to divert greywater away from the OSSs, possibly diluting phosphorus contents (Mkude et al. 2019).

Collectively, the estimated FS-derived compost analyzed in this study is 49.9 tonnes/d. The recommended national fertilizer application rate in agricultural land of Tanzania is 7 kg/ha (Benson et al. 2012). Based on that, the obtained amount is equivalent and could be enough for application in 7,128 hectares.

In terms of compost nutrients content, the *NutRec* scenario analyzed by the REVAMP tool indicates that, the obtained amount of FS-derived compost has 9% nitrogen content. However, the most common chemical fertilizer consumed by local farmers in Tanzania is urea which contains 46% of nitrogen (460 kg of nitrogen in 1 tonne of fertilizer) (Chianu and Chianu 2012). Therefore, the faecal sludge-based compost from this study could only substitute 19% of the nitrogen compared to urea. Based solely on the nitrogen content, FS-derived compost is therefore not a fully viable alternative to urea for direct plant growth improvement. However, it could be used as a soil conditioner instead to improve soil texture, permeability and porosity (Benson et al. 2012, Chianu and Chianu 2012, Harder et al. 2019).

Results from *EnRec* scenario were compared with the wood charcoal energy value of 32 MJ/kg at the current consumption rate in Dar es Salaam to be 79.79 t/day (Mwampamba 2017). When adopted the hypothetical FS energy value of 16.2 MJ/kg (Diener et al. 2014), results imply that the energy potential of FS-derived briquettes would substitute an average of 11.3% of wood charcoal by mass and 50% of the energy value. In other words, to reach the energy value required, two portions of FS briquettes would be needed to substitute a single portion of wood charcoal (thus, a 2 kg briquette is equivalent to 1 kg wood charcoal).

Potential economic benefits from recovered products

Potential revenue from products sales

It is important to note that the revenue obtained in this study considers only the direct sales of the FS derived products at local market prices during the study period. The estimated daily revenues generated from FS-derived products as analyzed based on Equations 3 and 5 are summarized in Figures 4 and 5.

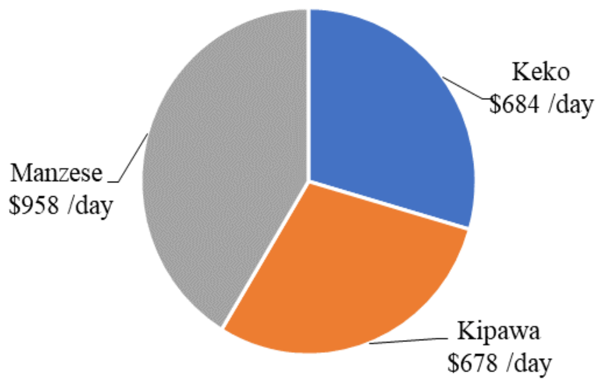

Figure 4: Daily revenue generated from potential sales of FS-derived solid fuel.

As shown in Figure 4, Manzese shows most potential revenue generation with the highest daily amount generated from direct sales of solid fuel, about 28% more than other areas. Again, this might be attributed to the fact that the largest amount of solid fuel with high calorific value is generated by FS from pit latrines which is more biologically unstable than that of septic tanks.

Furthermore, the economic values of compost products were from composted organic waste-alone, and co-composted FS and organic waste. As seen from Figure 5, the product from the co-composting generates more profit across all the study areas than that other from organic waste material alone.

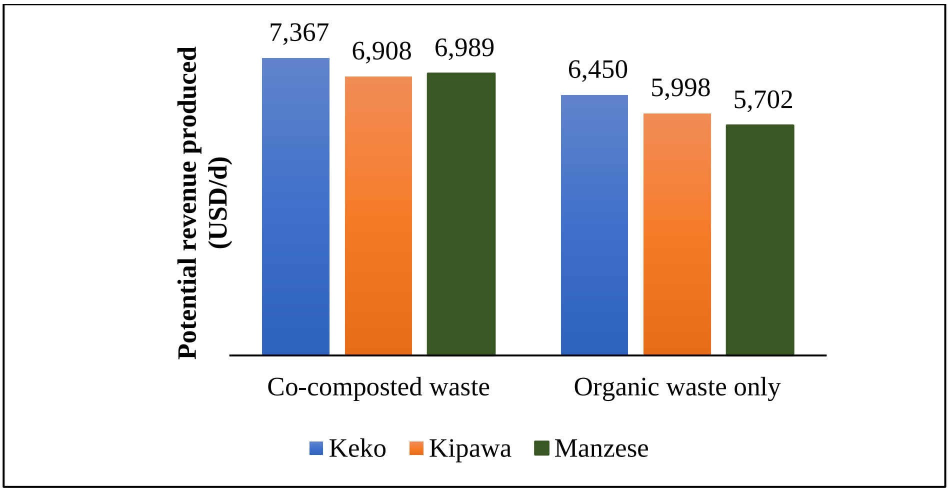

Figure 5: Potential revenue generated from sales of compost products.

The revenue analysis shows the variations of daily profit generated from compost materials. The minimum revenue can potentially be generated by composting organic waste alone, while the addition of faecal sludge increased revenue to the maximum of 7,000 USD. In general, the revenue obtained from compost product is way higher than of FS derived briquettes which generated a highest daily profit of just below 1,000 USD. The findings from this study are in line with other reported results showing composting of FS offers a business and development opportunity that could benefit millions of farmers (Rao and Otoo 2017). In Kampala, Uganda, for example, FS has been commonly sold for agriculture purposes from 5 USD to 10 USD per tonne (Ddiba 2016). A study by Gold et al. (2014) also showed that the community interest in using FS as a soil conditioner in urban areas of Sub-Saharan Africa is higher than other FS-derived products with the highest revenue possibilities. It is therefore important when considering composting FS has to be mixed with other organic wastes to ensure a steady volume and good quality of matured end-product (Esrey et al. 2001).

Potential saved costs from desludging and disposal

The current minimum desludging costs averages to 100,000 Tsh (44 USD) per pit and a minimum FS disposal fee of 10,000 Tsh (4.4 USD) for a vacuum tanker of 6000 litres capacity (0.73 USD per m^3 of FS) paid to the city's WSP facilities by emptiers (Seleman et al. 2020). At the same time, the average desludging rate of once in three months or four times per annum has been reported (Mkude et al. 2019). With an improved resource recovery of FS throughout the sanitation value chain, part of these costs which are financial burdens for tenants and land lords at the household level could be reduced or avoided altogether. Results of the potential costs saved from FS resource recovery in the study areas (See Equation 9) indicate an estimated daily saving of 152 USD, 150.8 USD and 213 USD from Keko, Kipawa and Manzese, respectively. These funds could then possibly be used to offset operations and maintenance (O & M) costs for the future resource recovery treatment plants.

Environmental benefits

Besides the presented economic benefits from FS resource recovery, additional environmental benefits could be linked beyond the sanitation system. The use of FS-derived briquettes as an alternative to wood charcoal has opportunity to contribute to mitigate climate change by combating deforestation. In this study, the total forest areas that could be saved by substituting FS-derived briquettes for wood charcoal were calculated and results are summarized in Figure 6.

Collectively, the annual quantity of FS-derived briquettes produced from the three study areas could substitute an average of 15% of the wood charcoal currently used for cooking in the settlements. This substitution suggests an estimate of 5 hectares of forest land that could potentially be conserved per year.

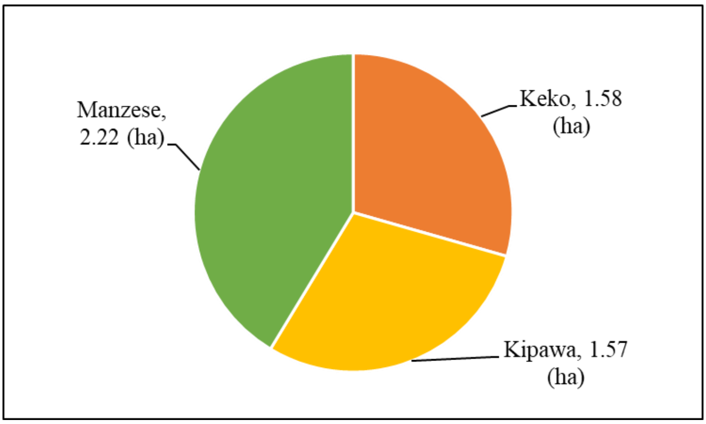

Figure 6: Forest areas (ha) that would be saved by using FS-derived briquettes produced.

Conclusions

Two scenarios developed and analyzed the recovery of resources from faecal sludge for the economic and environmental benefits. The analysis by REVAMP tool indicated the possibilities of recovering both nutrients and energy from collected faecal sludge in Dar es Salaam City. Results further revealed the daily production of compost materials for soil conditioning in agricultural land enough to substitute 19% of nitrogen obtained from urea fertilizer. The produced solid fuel could be able to substitute 15% of wood charcoal currently consumed and covers 50% of energy content. The study hence recommends that in order to obtain briquettes with high calorific value, FS should be co-fuelled with other feedstock char materials such as sawdust and rice husks. Economically, the compost was found to be more profitable than solid fuel. Compost was therefore recommended to be advocated when planning for faecal sludge resource recovery. Yet, in order to start FS resource recovery and reuse process towards the safety and health aspects of handling and manufacturing FS-derived products needs, more attention and guidelines and standards for safe re-use of FS derived products should therefore be developed and adopted.

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Competing interests
The authors declare they have no competing interests.

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