Quantification of economic and environmental benefits of faecal sludge derived compost and briquettes using a REVAMP tool: The case of Dar es Salaam, Tanzania

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Research

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Quantification of economic and environmental benefits of faecal sludge derived compost and briquettes using a REVAMP tool: *The case of Dar es Salaam, Tanzania*

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Abstract

In recent years, the concept of resources recovery from waste particularly faecal sludge (FS) has gained much attention and popularity. The aim of this study is to quantify/estimate the economic and environmental benefits of nutrients and energy that could be recovered from FS. The empirical data came from three unplanned settlements of Dar es Salaam City; Keko, Kipawa and Manzese. Two different FS resource recovery scenarios were assessed, namely nutrients and energy. The resource value mapping (REVAMP) tool was used to quantify benefits of nutrients and energy/solid fuels recovered from FS. The results indicate a daily economic benefit from FS recovery ranging between 680-950 USD for energy and up to 7,000 USD for nutrients recovered, depending on the composition. The co-composting of FS with organic waste to recover nutrients was found more profitable than FS derived briquettes. The environmental benefits, beyond the disposal of untreated FS into the local environment, include a potential saving of up to 5 hectares of forest area when substituting the use of wood charcoal with FS-derived briquettes for domestic cooking energy needs. Even here, co-composting FS is estimated to be more profitable than FS derived briquettes. The study concludes that to obtain FS derived briquettes with high calorific value, FS should be co-fuelled with other feedstock materials. Guidelines and standards for safe re-use of FS derived products should be developed, adapted and information campaigns and demonstration sites to illustrate the economic and environmental benefits of resource recovery from FS for energy and agricultural purposes should be made available to relevant stakeholders.

Keywords: *Faecal sludge; Resource recovery; Resource value mapping; REVAMP; Environmental; Economic, briquettes; compost; energy; nutrients*

1. Introduction

In the world of scarce resources, several alternatives have been explored to meet the growing resource demand. Resources recovery and reuse from waste is one of the alternatives under considerations. Resource recovery and reuse (RRR) is a new dimension in sanitation management that focuses on optimizing resource use and connect to water, energy and food systems [1]. Contrary to linear waste management solutions focus on treatment for disposal, the RRR concept is circular and attempts to ‘close the sanitation loop’ and turn human waste into a valuable resource [2]. RRR is particularly applicable in areas dominated by Onsite Sanitation Systems (OSS). In Dar es Salaam (DSM), Tanzania, about 90% of its inhabitants of 5 million, depend on onsite sanitation systems (OSSs) like pit latrines and septic tanks for their sanitation services and needs. A study from 2015 estimated that only about 43% of the collected faecal sludge (FS) from the city’s OSSs are safely managed by two designated Waste stabilization ponds (WSPs) located at Vingunguti and Buguruni areas [3]. A piled-up semi-solid faecal sludge, partially treated in WSPs needs proper and adequate management to ensure safe disposal without posing any environment and human health risks [4]. Various options for sustainable Faecal Sludge Management (FSM) have been developed in the last 10 years that makes it possible to safely and sustainably recover FS resources to be used as plant nutrients, water for irrigation, energy, and protein for animal feed [5].

The positive impacts of proper FSM through resources recovery have been widely documented. Reducing and averting nutrient loads causing eutrophication due to disposal of FS into water bodies is a major environmental benefit from increased FS-RRR [6]. RRR also when mainstreamed in FSM strategies, has the potential to contribute to achieving several sustainable development goals (SDGs) such as improving soil fertility and animal feed options to ensure food security (SDG2), provide renewable energy sources to contribute to energy security (SDG8), reduce risks of waterborne diseases to improve human health and safe management of sanitation (SDG3 and SDG6) as well as reduce environmental degradation (SDG15) [7]. Moreover, RRR could also have economic value by creating job opportunities and generated incomes from sales of end products [8]. When practised in the back-end of the sanitation value chain, FS-RRR has been proved to increase the sustainability of FSM by off-setting a portion of the treatment and disposal costs [4]. 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 [8]. For example, in Dakar, Senegal protein recovery appears to be more financially viable than other end-products; while in Kampala, Uganda, FS derived solid fuel was found to be more profitable than other products and in Accra, Ghana biogas currently has more biggest market value [5]. To ensure the most viable and sustainable end-product it is therefore important to assess not only the FS amount and nutrient content within the sanitation value chain but also the economic and environmental values of the anticipated end-product [9].

While the practice of FS-RRR in DSM is still at infancy stage, lacking information on economic and environmental benefits of produced FS-based products, therefore research on the potential and possibilities of FS-RRR has begun. In a study by Mkude et al., [10] the FS characteristics and available volume was estimated to determine the resource recovery potential from OSSs in three unplanned settlements of DSM. Drawing on the same data, 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).

2. Methodology

2.1 Study design

The study employed a cross-sectional research design combining both qualitative and quantitative methods during data collection and analysis. The quantitative method included a household survey and observation of available resource recovery practices and products in study areas. Qualitative methods involved key informant interviews and focus group discussions (FGD) with key stakeholders involved in faecal sludge management in Dar es Salaam. Furthermore, as a continuation study, results from preliminary analysis on faecal sludge amount and nutrients content from study areas documented by Mkude and others (2019) [10] were used as main inputs for quantification of recovery products.

2.1.1 Description of the study site

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 [11]. The areas were considered due to almost all population (99.2%) depend on OSSs including pit latrines and septic tanks for their sanitation services and needs [10]. To fulfil the populations' water and sanitation needs, two main water sources serve domestic needs through communal water standpoints for surface water and private and public boreholes for groundwater sources. 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.

2.2 Study approach

2.2.1 Resource Recovery Scenarios Analysis

i. Zero or Baseline Scenario

The status quo of FSM in DSM does not consider resource recovery. The same situation was used in MFA to present amount of FS and nutrients contained from collection to disposal.

ii. A scenario for a Change

This article considers two scenarios to represent hypothetical future resources recovery in DSM. The two scenarios include first, energy recovery (*EnRec*) via production of FS-derived briquettes to be used as domestic cooking fuel and second, nutrient recovery (*NutRec*) via compost production to be used as fertilizer in agriculture (see Figure 1).

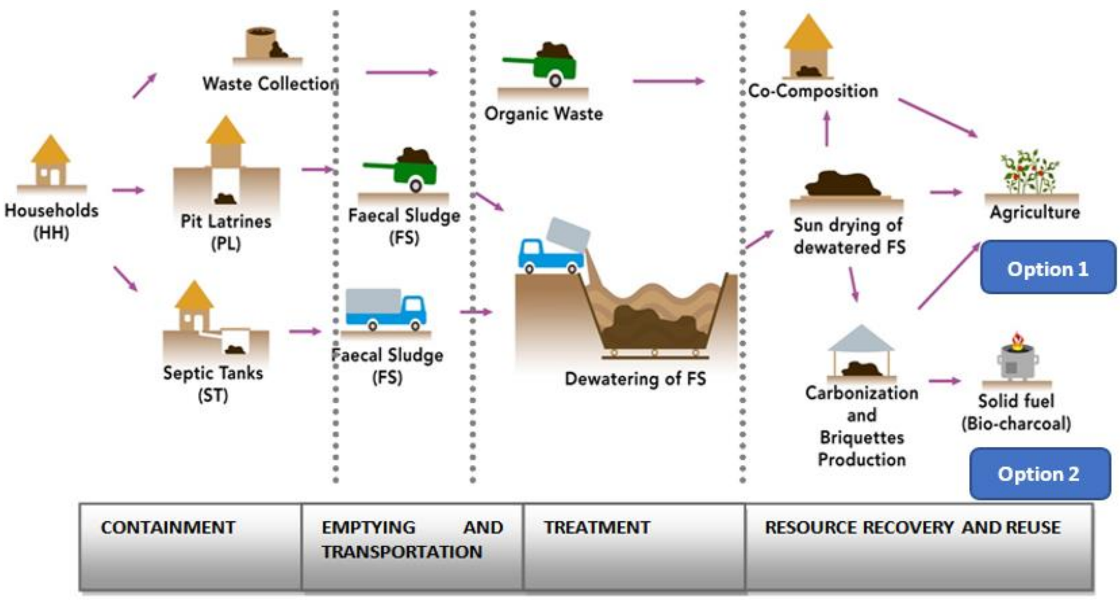
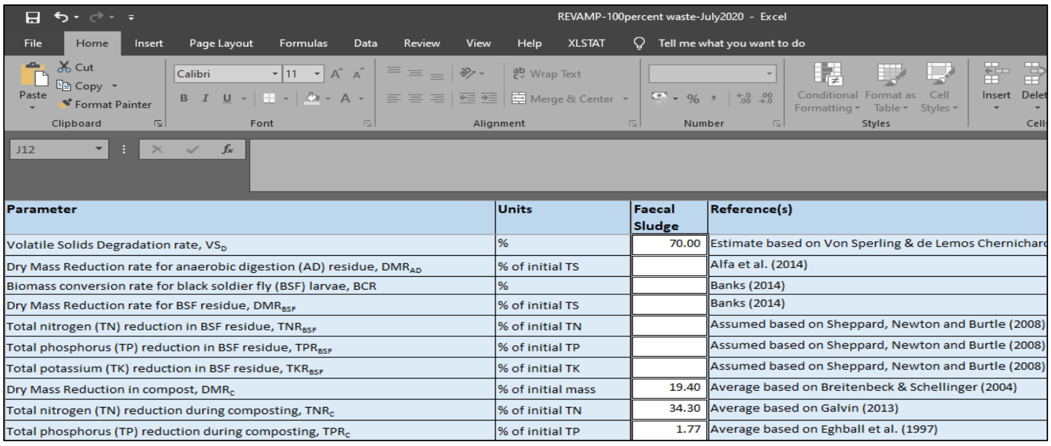


Figure 1. Schematic presentation of proposed resource recovery scenarios; co-composting and solid fuel production

The *EnRec* scenario considers the possible use of solid fuels as an alternative cooking fuel to the dominant wood charcoal currently used by the majority of residents in the study areas. The *NutRec* scenario considers the possible use of composted FS as an alternative or supplement to UREA fertilizers and other organic and animal waste currently applied by local farmers to improve soil fertility [12]. To obtain a higher nutrient content level, FS was co-composted as recommended by Tayler, [13]. Accordingly, in the NutRec scenario, FS was co-composted with organic waste, sorted from collected municipal solid waste, due to its availability throughout the year. The end products were analyzed and presented in the REVAMP tool and compared based on mass volume and revenue.

2.2.2 Resource Value Mapping (REVAMP) tool

The resource value mapping (REVAMP) is a tool developed as a Microsoft Excel spreadsheet with built-in formulae that consists of six (6) working sheets. The tool was developed by Stockholm Environmental Institute (SEI) for rapid estimation, visualization and valuation of the potential resources to be recovered from organic waste streams in urban areas. The tool includes both sewage sludge, faecal sludge, as well as food and other organic solid waste [14]. 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 [15]. Figures 2 (a) and (b) displays examples of REVAMP tool computer interfaces.



Parameter	Units	Faecal Sludge	Reference(s)
Volatile Solids Degradation rate, VS_D	%	70.00	Estimate based on Von Sperling & de Lemos Chernichar
Dry Mass Reduction rate for anaerobic digestion (AD) residue, DMR_{AD}	% of initial TS		Alfa et al. (2014)
Biomass conversion rate for black soldier fly (BSF) larvae, BCR	%		Banks (2014)
Dry Mass Reduction rate for BSF residue, DMR_{BSF}	% of initial TS		Banks (2014)
Total nitrogen (TN) reduction in BSF residue, TNR_{BSF}	% of initial TN		Assumed based on Sheppard, Newton and Burtle (2008)
Total phosphorus (TP) reduction in BSF residue, TPR_{BSF}	% of initial TP		Assumed based on Sheppard, Newton and Burtle (2008)
Total potassium (TK) reduction in BSF residue, TKR_{BSF}	% of initial TK		Assumed based on Sheppard, Newton and Burtle (2008)
Dry Mass Reduction in compost, DMR_C	% of initial mass	19.40	Average based on Breitenbeck & Schellinger (2004)
Total nitrogen (TN) reduction during composting, TNR_C	% of initial TN	34.30	Average based on Galvin (2013)
Total phosphorus (TP) reduction during composting, TPR_C	% of initial TP	1.77	Average based on Eghball et al. (1997)

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Figure 2(a). The REVAMP tool interface estimating waste streams treatment processes

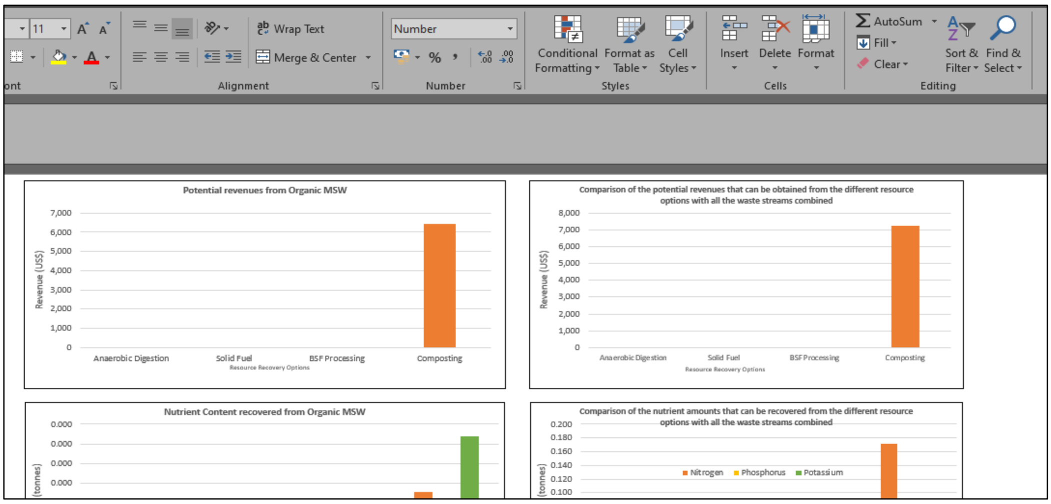

Figure 2(b). The REVAMP tool interface displaying final results

2.2.3 Steps followed in the application of REVAMP analysis

In the first step, all the required data according to the waste streams used for analysis were filled in the data input sheet separately for each study area. Composting and solid fuel production were selected among treatment processes based on two resource recovery scenarios. Prices of products were identified from the literature review and interviews with Key Informants. Table 1 presents benchmark information including the fraction of faecal sludge amount emptied and delivered to treatment plants and estimated nutrients flows calculated by MFA [10].

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	[11]
Fraction of pit latrines out of OSSs, %	27.1	35.9	61.8	[9]

Fraction of septic tanks out of OSSs, %	72.1	63.4	38.2	[9]
Volume of FS delivered to treatment plants (l/ca/yr)	408.80	434.35	646.05	[9]
Nitrogen (tons/yr)	293.91	318.70	359.48	[9]
Phosphorus (tons/yr)	29.95	23.03	28.59	[9]
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

2.3 Data collection method

Data collection took place between September 2017 and November 2018. A total of 395 respondents participated in the household survey, 19 key informants were interviewed and six focus group discussions and observations were conducted in all three study areas. A literature review and field observations were carried out to obtain an overview of OSS facilities and population served as well as the faecal sludge contents potential for recovery. Focus group discussions, key informant interviews and household surveys identified availability of and prices for different energy and nutrient products.

The amount of FS generated and transported along the sanitation service chain was then quantified in each locality, drawn from the Material flow analysis (MFA) technique and using the Software for Substance Flow (STAN). The MFA was used to trace and quantify the annual FS generated, stored and deposited together with nutrients (nitrogen and phosphorus) contained in FS from three study areas [10].

2.4 Data analysis using the REVAMP tool

The input data were obtained from different data collection methods representing a status quo (no changes) scenario. The tool incorporates different built-in mathematical expressions in the quantification of the desirable end-products according to the waste streams used. Apart from the general information that cut across each study area, data analysis for each recovery option was conducted based on eight (8) equations by Ddiba, 2016 [15]as expressed accordingly.

2.4.1 Potential amount of FS-derived briquettes

Energy recovery was sought to be achieved through the production of dried FS briquettes to be used for combustion. It is recommended that for the faecal sludge to be used as an energy source, needs 90% dryness [16]. Estimation of solid fuel amount by REVAMP was first given in mass (tonnes) then evaluated for its calorific value (energy content). The mass of briquettes (B_m) was obtained from the known volume of collected faecal sludge (FS_v) as shown in table 1 and volume of total solids (TS_v) in mg/l by using equation 1.

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

Then, the fuel energy content, E_F (MJ) was calculated based on calorific value (CV) of dry matter in MJ/kg TS, as recommended by Diener et al. (2014) using the Eq. 2

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

The revenue that can potentially be generated from the briquettes used was calculated based on a mass of briquettes in tonnes (B_m) and the price in US$/tonne ($F_p$) as;

Potential revenue from briquettes = $B_m(tonnes) \times F_p(US\$/tonne)$ (Eq.3)

Input data for EnRec scenario

Since the production and use of solid fuel from FS is still not common in Tanzania, particularly in Dar es Salaam, most of the input data related to faecal sludge-based briquettes was obtained from the literature. A Total Solids (TS) of 30,000 mg/l for dried FS was adopted [17]. The price of FS briquettes was lacking. Instead, the available and comparable solid energy source which is either wood charcoal or other biomass briquettes could be used. Since the wood charcoal is the dominant source used by more than 90% of the population, its cost was taken as alternative. Table 2 summarizes input data used for *EnRec* scenario.

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., [17]
2.	Faecal sludge calorific value	16.2 MJ/kg	Muspratt et al., [5]
3.	Cost of charcoal	0.60 US$/kg	Msuya et al., [18]
4.	Cost of biomass briquettes	0.26 US$/kg	Lohri et al [19]

2.4.2 Potential amount of FS-derived compost

The designed *NutRec* scenario was achieved through the co-composting of faecal sludge and organic waste fraction from municipal solid waste (MSW). Data of two waste streams; faecal sludge and organic waste were needed in the REVAMP analysis. Faecal sludge dryness of 60% is recommended to achieve composting and through the process, reduction of mass of combined waste streams is expected [15]. The value of dry mass reduction during the composting (Compost Mass Reduction-CMR) expressed in percentage (%) was obtained from the literature. The amount of compost, C_m (in tonnes) that can be obtained at 60% dryness, was calculated using equation 4.

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

The revenue that can potentially be generated from the compost if put on sale was calculated based on the mass of compost (C_m) and the price of compost fertilizer (C_p) according to Eq. 5.

$$\text{Potential revenue from compost} = C_m(tonnes) \times \text{C}_p(US\$/tonne) \quad \text{(Eq.5)}$$

When the sanitary waste stream is treated through composting, results in nutrients reduction. It was therefore, necessary to quantify nutrient content and consider the percentage of nutrient reduction during the co-composting (NR_C) of faecal sludge and organic waste (OW). The expected nutrient content in the compost, NUT_C (tonnes), was therefore calculated using Eq.6 for faecal sludge and Eq. 7 for organic MSW. Nitrogen and Phosphorus were the two nutrients analyzed in the analysis.

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

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

Where; NUT_C expresses the nutrient content, either Nitrogen or Phosphorus and OW_w is the weight of organic waste sorted from municipal solid waste.

The nutrient content in terms of percentages was calculated by the amount of each nutrient in the compost and amount of compost itself in tonnes according to Eq. 8.

Nutrient content in the compost (%) = $\frac{NUT_C\ (tonnes)}{C_m(tonnes)} \times 100$ (Eq.8)

Input data for NutRec scenario

In DSM, the average per capita solid waste generation rate has been reported to be 0.815 kg/cap/d out of 78% is composed of organic waste [20–22]. A market price approach was used to obtain the cost of organic compost through key informant interview. Other technical values were adopted from the literature. Such values included reduction of FS and organic solid waste dry mass and nutrients (NR) for nitrogen and phosphorus during composting was customised to fit the study situation. Table 3 presents a summary of input data specific for *NutRec* scenario 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	[20–22]
2.	Price of packaged compost	0.43 US$/kg	Interview, 2018 (UMAWA)**
3.	Total Nitrogen reduction from FS during composting, ($NR_{N\text{-}FS}$)	34.3% of the initial mass	Schoebitz et al., [17]
4.	Total Nitrogen reduction from OW during composting, ($NR_{N\text{-}OW}$)	50% of the initial mass	Galvin, [23]

5.	Total Phosphorus reduction during composting, (NR_P)	1.8% of the initial mass	Schoebitz et al., [17]
6.	Dry mass reduction in compost	19.4% of the initial mass	Breinenbeck and Schellinger [24]

** UMAWA (*Usafi wa Mazingira na Watu*), a local NGO, manage the DEWATS at Kigamboni, Dar es Salaam.

Other necessary assumptions made

- The total number of population in specific areas were adopted from 2017, forecasted from the last census of 2012 used in the calculation [11].
- Faecal sludge considered for resource recovery comes from both septic tanks and pit latrines. No separation of OSS types was taken into considerations.
- Amount of FS used was calculated from percentages of per capita generation rate of faeces, urine and greywater goes to OSSs, flowing along the sanitation service chain as reported in the sheet flow diagram of DSM [3].

2.5 Results implication and use from REVAMP

2.5.1 Economic benefits indicators of FS resource recovery

The economic values of resource recovery from faecal sludge were determined in two ways. One, the revenues calculated from potential direct sale based on known amount and price of products and second value was obtained from potential saved costs from FS desludging, transport, treatment and disposal [14]. The market value price was used to estimate the economic value. The currency exchange rate of 1 US$ = 2,277 Tshs from

15th November, 2019 was used in revenue calculations (www.bot.go.tz). Second, the economic benefits from diverting FS amount needed for recovery units were obtained from potential Total Cost (TC) to be saved as expressed in equation 9 modified from Rangga et al., [25].

$$TC = \sum [(\text{FS volume, } (m^3/yr) \times \text{desludged frequency, (month/year)} \times \text{Desludging fee, } (USD/m^3)) + (\text{FS volume disposed, } (m^3/yr) \times \text{Disposal fee, } (USD/m^3))] \quad \text{(Eq. 9)}$$

where, TC = total cost saved

FS = Feacal sludge

USD = United States Dollar

2.5.2 Environmental benefits indicators from resource recovery implementation

The environmental benefits of applying RRR was analysed as one among contributions in combating deforestation. It was evaluated by estimating the forest area saved. The area that would be saved from wood charcoal production by substituting with solid fuel was obtained as explained by Mwampamba [26].

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

Where;

M_s is the mass of single sack contains charcoal (kg of charcoal/sack),

E_k is the 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. The efficiency of traditional unimproved earth kilns commonly used in Tanzania perform at 10% efficiency [18]. The average stock density is 66 t/ha [27]. Not all 100% of the forest is harvested for wood charcoal, hence 93% of stock density is suggested for calculation purposes [26].Using the formula expressed as Eq.10 and adopted parameters, the forest area needed to produce 1 tonne of charcoal is 0.00162 ha.

3. RESULTS AND DISCUSSION

3.1 Nutrients and Energy contents in FS from study areas

Results displayed from the REVAMP tool present daily nitrogen and phosphorus as well as energy amount available in FS for recovery. Based on the amount of FS collected and delivered to treatment plants from each study area, the daily potential nutrients and energy content is estimated and presented in a combined bar and scatter plot chart (Figure 3).

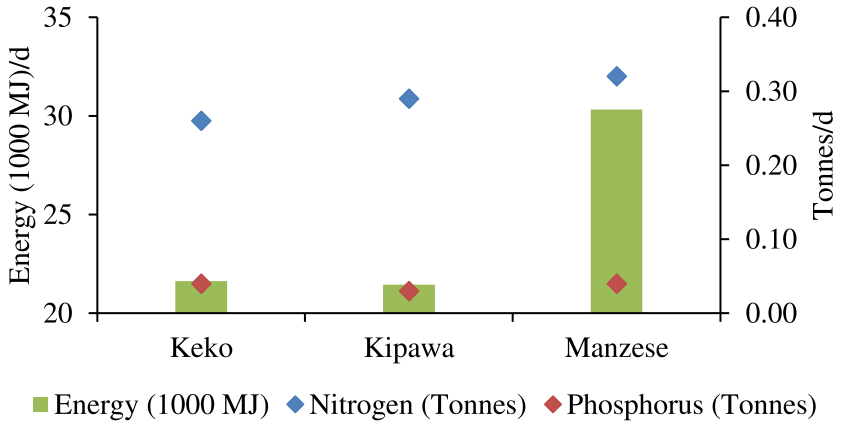

Figure 3. Nitrogen, phosphorus and energy content estimated from the available daily amount of FS

The findings show that the largest amount of nitrogen could be obtained from Manzese, about 29% more than Keko and Kipawa. This could be explained by the fact that Manzese is predominantly served by pit latrines. Pit latrines contain undiluted and relatively slowly digested FS as compared to septic tanks [28–30]. The accumulation and dispersion mechanisms which determine the nitrogen and phosphorus concentrations are slow in pit latrines as compared to septic tanks [31]. Similarly, 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.

3.3 Analysis of resource recovery scenarios

3.3.1 Potential amount of composted FS and solid fuel generated

In the first analysis composted FS and solid fuel production was based on 100% of faecal sludge, without any other organic waste (OW). Here the results indicates that Keko has the possibility of producing significantly larger amounts of compost compared to Manzese and Kipawa. In the second analysis, co-composting was performed by mixing FS with OW, calculated from the per capita generation rate. As expected, the largest amount of co-composted FS thus comes from the most populated area, Keko, here a possible total daily amount of 49.9 tonnes could be produced, with a nutrient composition of 9%, 6% and 0.4% for nitrogen, phosphorus and potassium respectively.

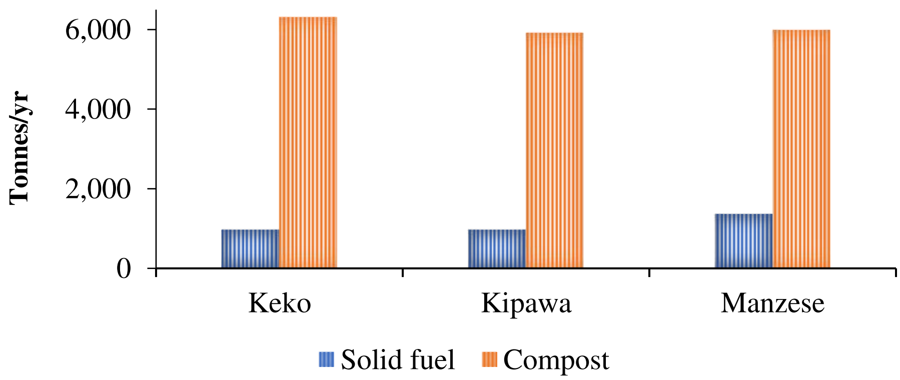

Figure 5. Amount of compost and solid fuel produced per year in the study area

The total annual amount of solid fuel generated across the study areas are 3,310.55 tonnes equivalent to 9.07 tonnes per day. 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 [19]. There were no additives which were added as the case for composting which could also enhance the addition in mass for the final product obtained.

Generally, the findings show that the availability of nutrients (nitrogen and phosphorus) contents from FS which can be recovered for agricultural purposes is high. 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 source of phosphorus content in OSSs could be from soap and detergents used in cleaning and personal health care products [6]. Moreover, the majority of houses in this study were observed to divert greywater away from the OSSs, possibly diluting phosphorus contents [10].

The collective estimated FS-based compost from produced in this study, resulted in 49.9 tonnes/d. The recommended National fertilizer application rate in agricultural land of Tanzania is 7 kg/ha [12]. Based on that, the obtained amount is equivalent to and could be enough for application in 7,128 hectares.

The *NutRec* scenario analysis indicates that in terms of nutrients content, the obtained amount of FS-based compost analyzed in the REVAMP tool 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) [32]. 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-based compost is therefore not a viable alternative to UREA to improve direct plant growth. However, it could be used as a soil conditioner to improve soil texture, permeability and porosity [33].

Results from *EnRec* scenario analysis were compared to the 32 MJ/kg energy value of wood charcoal [26,34]. The calculations include the hypothetical FS energy value of 16.2 MJ/kg and the maximum energy content of 30,000 MJ obtained in Manzese. The results indicate that the energy potential of FS-based briquettes would only substitute an average of 15% 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 (e.g. 2kg briquettes equivalent to 1 kg wood charcoal).

3.3.2 Potential Economic Benefits from Recovered Products

Potential revenue from products sales

It is important to note that the revenue obtained in this study considers the direct sales of the FS derived products at local market prices during the study period. There were no additional revenue adjustments done linked to crop yields increase from application of FS-derived soil conditioners on agricultural land. For the FS-derived compost the average price was based on estimates obtained during the interviews while the price of FS-derived briquettes was estimated in comparison to wood charcoal. The estimated daily revenue generated from FS based products from possible direct sales was then analyzed based on equations 3 and 5 with summarized results in figures 6 and 7.

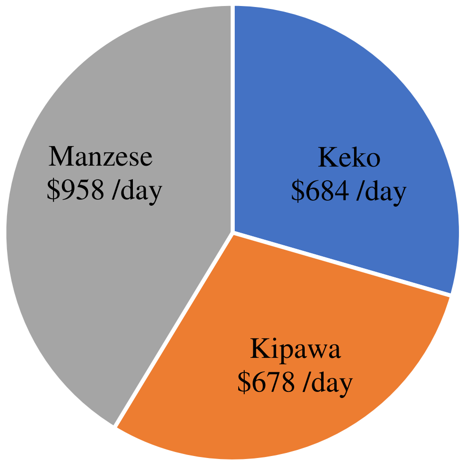

Fig 6. Daily revenue generated from potential sales of FS-based solid fuel

As shown in figure 6, Manzese shows the potential for the highest daily revenue 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 FS from pit latrines which is more biologically unstable than that of septic tanks.

Furthermore, the economic value of compost was compared from composted FS-alone, OW-alone, and co-composted FS and OW. As can be seen from Figure 7, the products from the co-compost waste generates more profit across all study areas than other compost materials. The products from individual waste material were the least profitable.

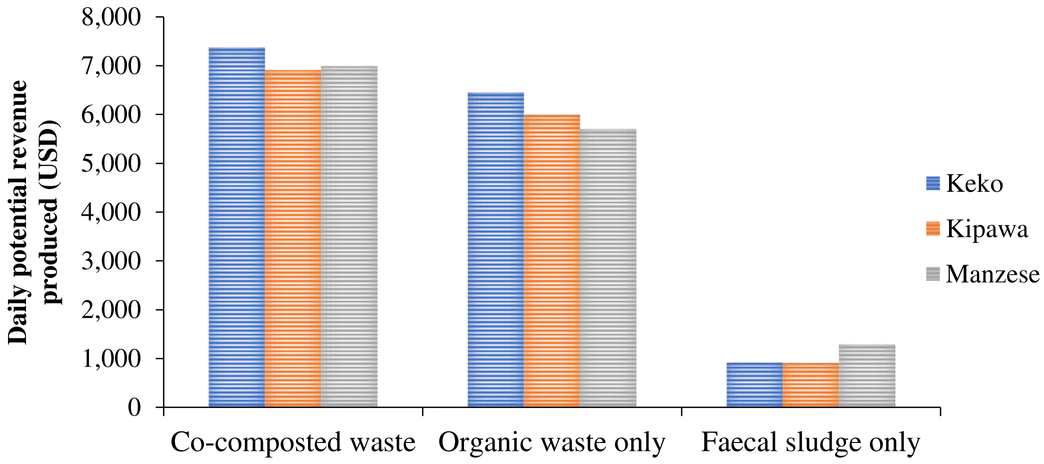

Figure 7. Potential revenue generated from sales of compost products from different waste materials

The revenue analysis shows the variation of daily profit generated from compost material. The minimum revenue ranges 900 -1300 USD can potentially be generated by composting faecal sludge only while the revenue increased to the maximum of 7,000 USD as different waste streams co-composted together. The revenue obtained from compost product is slightly higher than from FS derived briquettes which its highest daily profit generated was below 1,000 USD. The findings from this study are in line with the results reported in other studies that composting of FS offers a business and development opportunity that could benefit millions of poor farmers [2]. Kampala, Uganda, for example, FS has been commonly sold for agriculture purposes from 5 USD to 10 USD per tonne [15]. Research by Gold et al., [4] also show that the interest in using FS as a soil conditioner in urban areas of Sub-Saharan Africa is higher than other FS-based products. Indeed, it has been estimated that if all FS collected in the city of Dakar, Senegal and Kampala, Uganda was sold as soil conditioners it could generate a gross value of USD 12,480/year in Dakar and USD 81,120/year in Kampala. When compared to the revenues of FS-derived briquettes indicating and even higher profitability compared to soil conditioners [33]. In this particular case this was possible because the primary consumers of the briquettes were private sector companies buying them in bulk as an energy source to fuel industrial processes

When considering composting it has been shown that when FS is mixed with other OW it has the highest revenue possibilities [35]. This is because co-composting can ensure a steady volume and quality end-product [36]. This finding needs to be taken into considerations when planning for resource recovery through composting.

Potential saved costs from desludging and disposal

In the studied sites and Dar es Salaam at large, costs for FS desludging and transport remains a heavy financial burden for tenants and land lords at the household level and the discharge fees at the disposal points are incurred by service delivery entities [37]. With improved resource recovery of FS throughout the sanitation value chain part of these costs could be reduced or avoided altogether [38]. Currently households in the study areas reported an average desludging rate of once every three months or four times annually [10]. Today the minimum desludging costs averages 100,000 Tsh (44 USD) per pit plus 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 by emptiers to the city's WSP facilities. Calculations of the potential costs saved from FS resource recovery in the study areas (See Eq. 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 linked with running future resource recovery treatment plants that would benefit both individual households and the city as a whole

3.3.3 Environmental Benefits

Besides possible economic benefits from FS resource recovery and improving FSM, additional environmental benefits could be linked beyond the sanitation system itself. The use of FS-based briquettes as an alternative to wood charcoal has opportunity to contribute to mitigate climate change, by combating deforestation. In this study, the total forest area that could be saved by substituting FS-derived briquettes for wood charcoal has been calculated in equation 10 and the results are summarized in Table 4.

Table 4. Forest area that would be saved by using FS based briquettes produced

Study area	Annual Mass of briquettes produced (tonnes/yr)	Equivalent Forest area saved (ha)
Keko	974.55	1.58
Kipawa	967.25	1.57
Manzese	1,368.75	2.22
TOTAL	**3,310.55**	**5.37**

Collectively, the annual quantity of FS-based 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 estimated 5 hectares of forest land that could potentially be conserved from being cut down per year.

4. CONCLUSIONS

Two scenarios analyzing the recovery of nutrients and energy from FS for agricultural and domestic uses respectively were quantified for economic and environmental benefits. Analysis from REVAMP indicates the possibilities of recovering nutrients as well as energy from collected FS. Results further revealed the possibility of recovering nutrients with a daily total production of 49.9 tonnes of composted fertilizer. This amount is enough to substitute 19% of nitrogen obtained from UREA fertilizer. Along with organic matter, the FS based compost could improve soil texture, porosity and permeability. These are benefits which cannot be realized using chemical fertilizers. The co-composting of FS with organic waste to recover nutrients was found to be more profitable than solid fuels. The produced 9.07 tonnes of solid fuel could be able to substitute 15% of wood charcoal consumed, covers 50% of energy amount. However, the revenue generated from both recovery options varied. Compost is more profitable than energy source. The study also found that to obtain briquettes with high calorific value, FS should be co-fuelled with other feedstock materials and co-composting should be advocated when planning for resource recovery through composting.

So far however, FS resource recovery practices across the African continent, and in Tanzania especially, is still rare, but case study research, including this one, indicates that there are both economic and environmental benefits to be had, beyond the likely positive impacts for FSM with significant reduction of untreated FS volumes entering and polluting local waterways and soils and posing human health risks. Yet, in order to start this process towards FS resource recovery and reuse the safety and health aspects of handling and manufacturing FS based 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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Authors' contributions

All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in submitted manuscript

Competing interests

The authors declare they have no competing interests.

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Figures

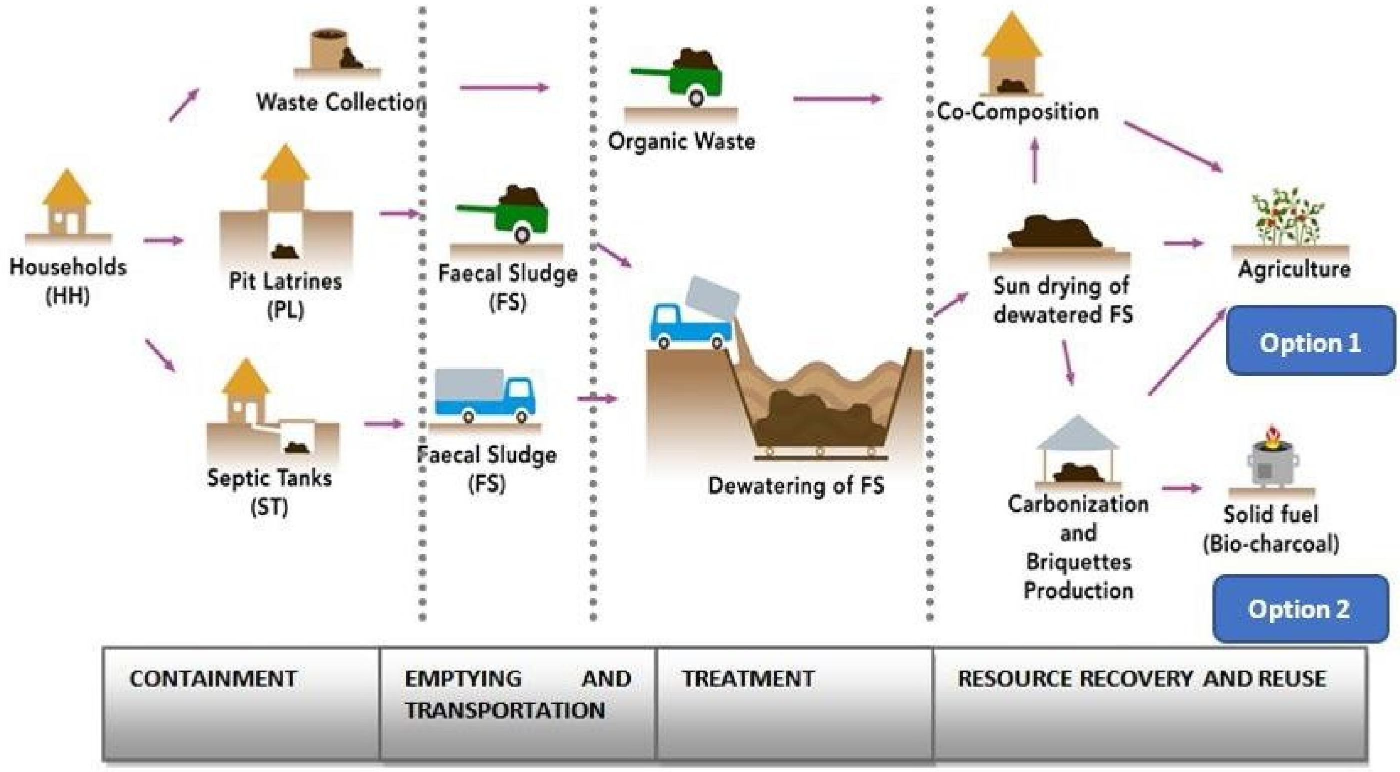

Figure 1

Schematic presentation of proposed resource recovery scenarios; co-composting and solid fuel production

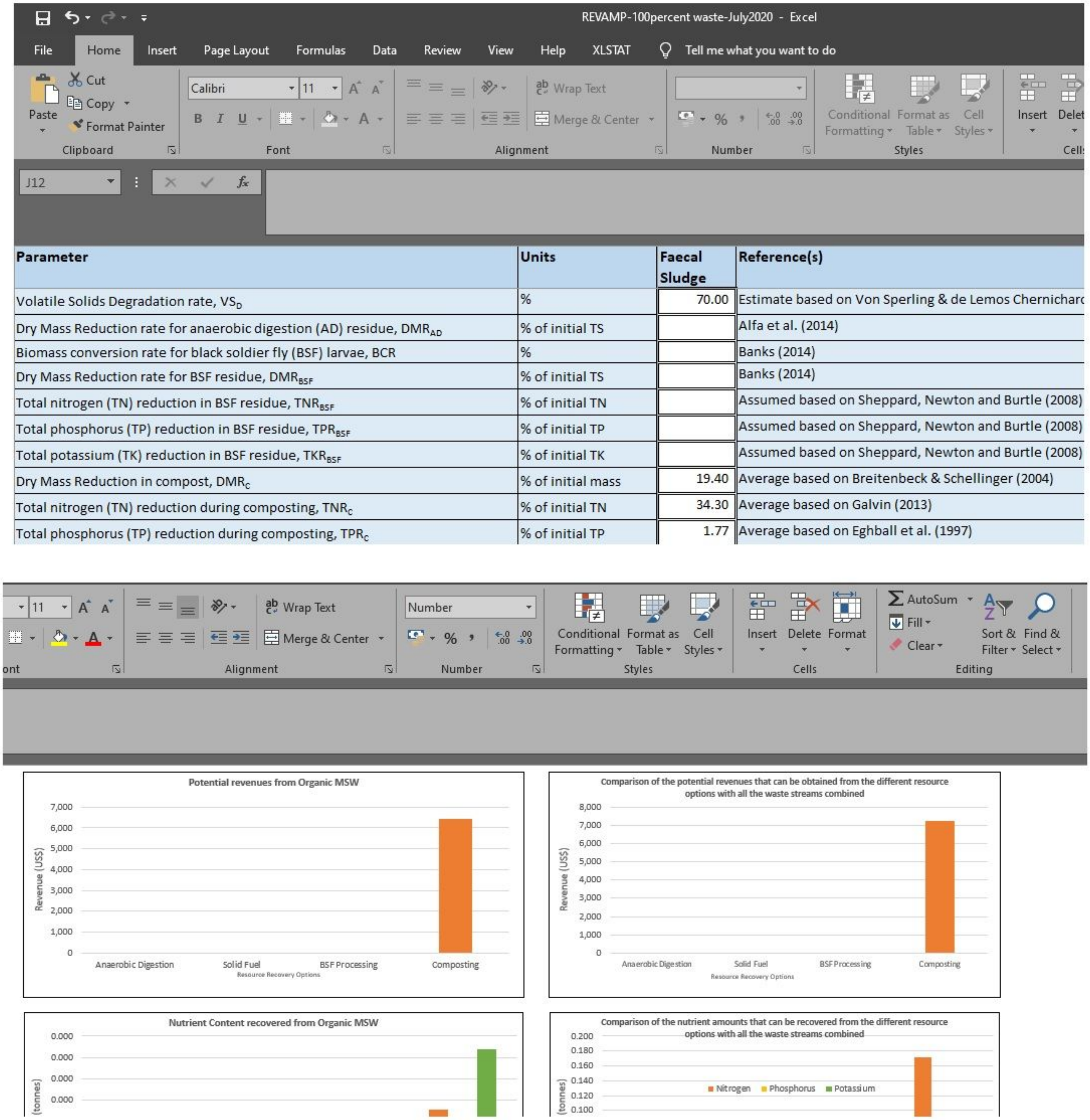

Figure 2

(a). The REVAMP tool interface estimating waste streams treatment processes (b). The REVAMP tool interface displaying final results

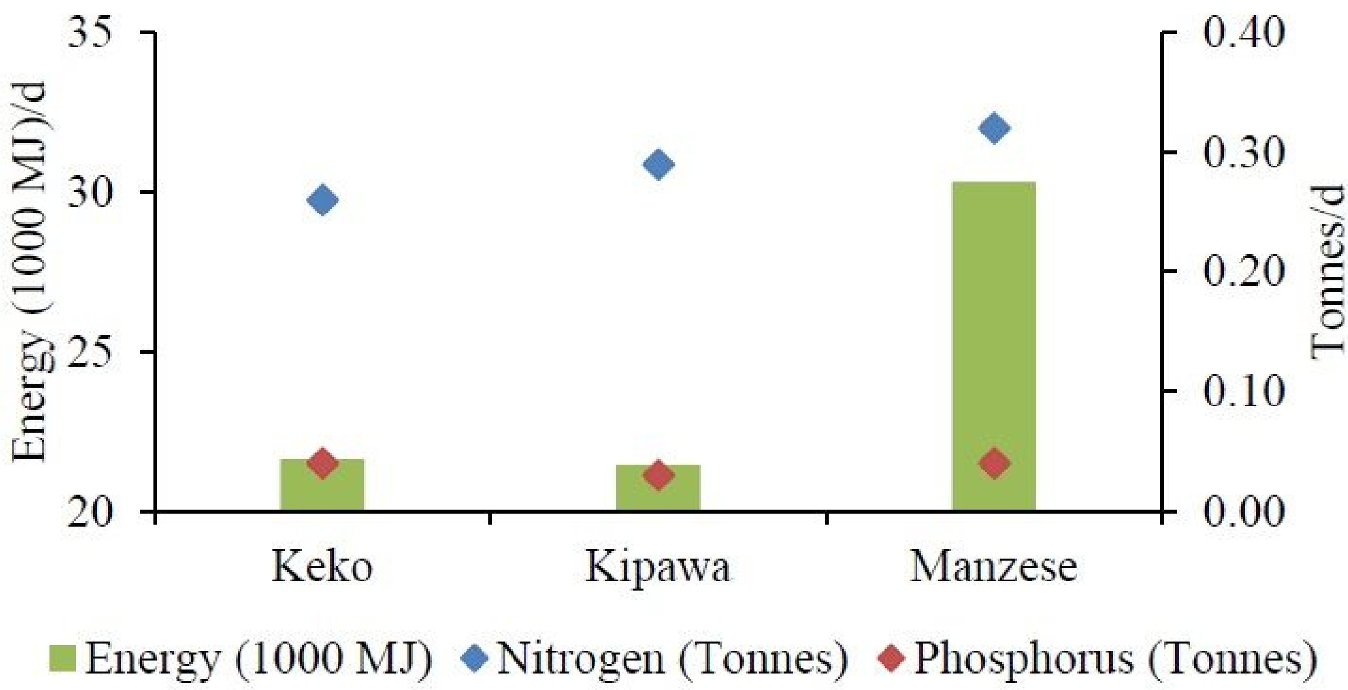

Figure 3

Nitrogen, phosphorus and energy content estimated from the available daily amount of FS

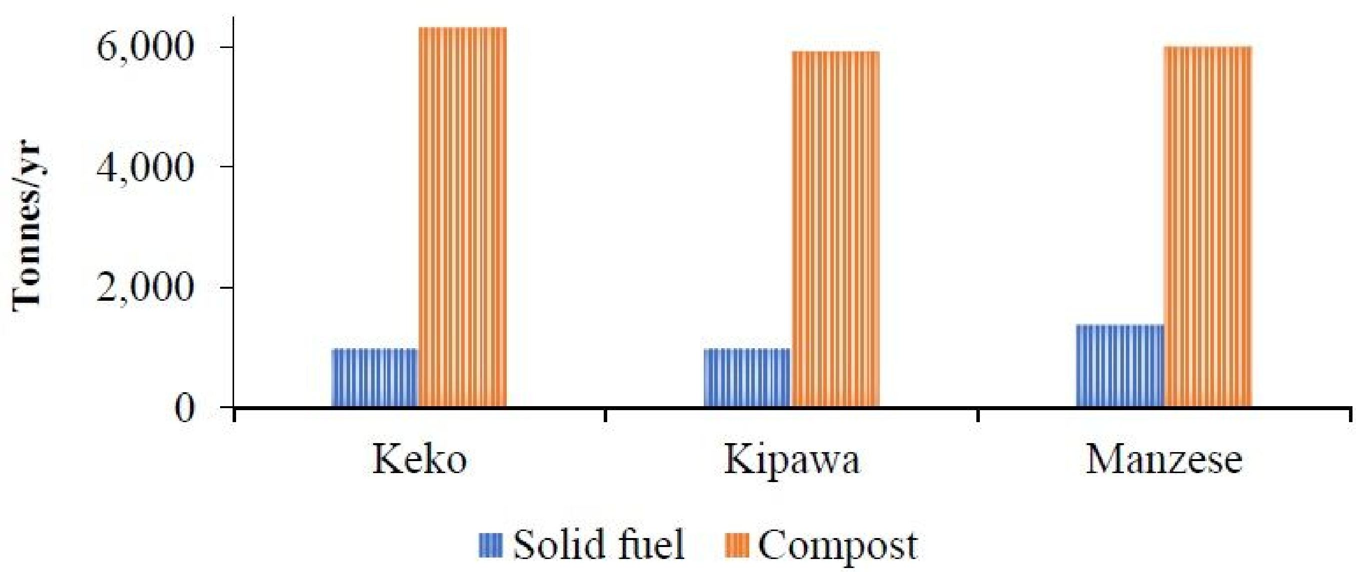

Figure 4

Amount of compost and solid fuel produced per year in the study area

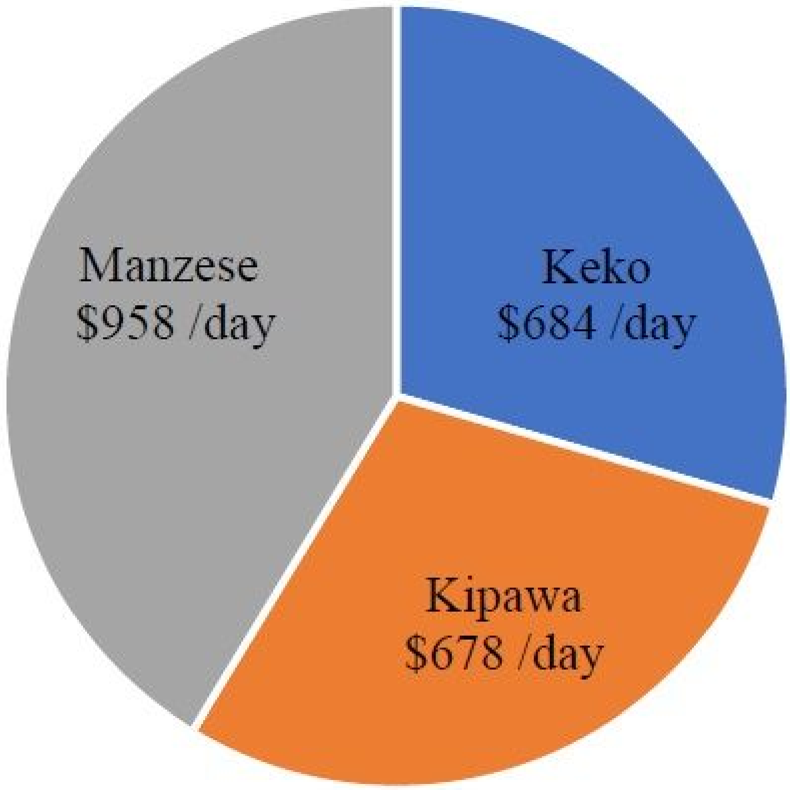

Figure 5

Daily revenue generated from potential sales of FS-based solid fuel

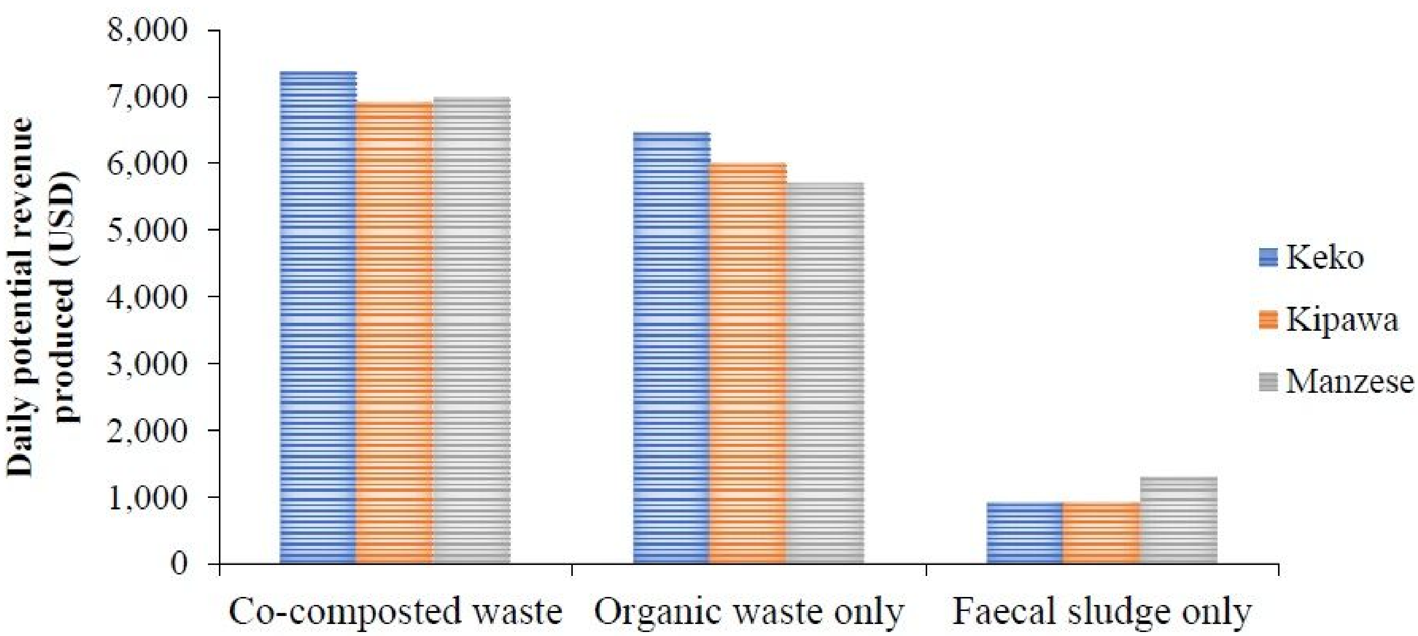

Figure 6

Potential revenue generated from sales of compost products from different waste materials