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# Safe resource recovery from faecal sludge: evidence from an innovative treatment system in rural Tanzania

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Globally, innovative treatment systems are needed to incentivise safe faecal sludge management practices and resource recovery. In rural Tanzania 83% of the population do not have access to basic sanitation. Communities rely on on-site sanitation (pit latrines) that are not safely managed and allow for faecal sludge to contaminate groundwater used for drinking. This study reports on the design and evaluation of a novel treatment system; dewatering of faecal sludge in solar drying beds, followed by capturing of faecal sludge leachate and leachate heat sterilisation using a rocket stove fired with agricultural waste. Faecal sludge was manually extracted from 25 pit-latrines in rural Tanzania and analyzed at 0.5 m depth profiles. For aged latrine sludge (1.5 m deep) the ratio of total volatile solids to total solids halved, indicating stabilization. However, densities of *Escherichia coli* remained elevated ($5.6 \times 10^4$ cfu $g^{-1}$). Extracted sludge was loaded (~0.9–1.35 $m^3$) into drying beds for 21 days and final *E. coli* densities were highly variable. The leachate was captured from drying beds in 150 L batches and took 40 min to heat to 98 °C in the rocket-stove with a rice husk fuel feeding rate of 48 kg $h^{-1}$. Heat treatment of leachate completely inactivated $3.1 \times 10^5$ cfu/100 ml of *E. coli* (5.5 $\log_{10}$ reduction) and reduced total coliforms by 99.9% (3.1 $\log_{10}$); reaching safe guideline values for unrestricted agricultural reuse. Thus, the stove is an innovative low-cost technology for treatment of faecal sludge for rural communities in developing countries that produces faecal products that can be safely used in agriculture.

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**Water impact**

Globally, 4.5 billion people do not have access to safely managed sanitation. New treatment technologies are needed to treat faecal sludge and enhance its value through resource recovery. A novel low-cost treatment system in rural Tanzania demonstrated that pit-latrine sludge could be effectively treated. The products of dried bio-solids and heat-sterilised leachate can be used safely by local farmers.

## Introduction

An estimated 4.5 billion people globally, do not have access to a safely managed sanitation service.[1] Further, 2.8 billion people use on-site sanitation which consists of pit-latrines, septic tanks, simple vaults or variants of these.[1] In sub-Saharan Africa (SSA), it is assessed that on-site sanitation (pit-latrines, septic tanks or simple vaults) are used by 84% of the urban population[2] and the vast majority of rural populations.[3] In SSA, only 46% of the population have access to improved sanitation (either basic or limited).[1] High levels of unimproved sanitation is estimated to attribute to 21% of the diarrhoeal disease burden; resulting in an estimated 126 294 deaths and 9.7 million disability adjusted life years (DALYs) in SSA in 2012.[4] The sustainable development goals (SDG) aim to increase access to a safely managed sanitation service (SDG 6.2) and also to halve the quantity of untreated wastewater being discharged into the environment (SDG 6.3).[1]

Safely managed sanitation service must have treatment *in situ*, removal and treatment off-site or be connected to a sewer system with a wastewater treatment plant.[1] For SSA there is very limited data on the portions of faecal sludge from on-site sanitation that are safely managed.[1] In some cities, as little as 35% of sanitation systems are safely managed.[2] In rural areas the proportions of treated faecal sludge are likely to be much lower, as there are fewer

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incentives to remove and treat faecal sludge, in part due to the availability of space to easily construct a new latrine when a latrine becomes full.[5] Research in rural Ghana reports that households do not empty latrines and would rather abandon a full latrine because; they did not want to use unhygienic manual emptying services that took a long time, the high-cost of mechanical pumping services and the lack of faecal sludge disposal sites in the community.[6]

Faecal sludge composition varies greatly between communities and depends on on-site containment types, construction methods used for latrines, different household use-age patterns, emptying frequencies, hydrogeology and batch extractions methods.[3,7] Due to these factors, the design of faecal sludge treatment plants is challenging and more data is needed on the quantities and qualities of faecal sludge in-order to inform initial engineering design calculations and operational guidelines.[8] There are growing examples of successful decentralized treatment systems that treat faecal sludge either on-site or from latrines in the surrounding area.[9] Dewatering drying beds have been used in urban Dakar, Senegal to treat septage (septic tank sludge) and public toilet faecal sludge and both the resulting bio-solids and percolate evaluated for local garden use.[10] Heat treatment technologies have been applied at small scale to treat wastewater,[11,12] sewage sludge[12–14] and pit latrines sludge,[15] to enable safe faecal sludge resource recovery or disposal. However, reliance on electricity is an expense and barrier to scaling up especially in rural areas. Hence, heat treatment methods for faecal sludge that are low cost and do not require significant input of electricity or materials are needed.

There are a number of resources that can be recovered from faecal sludge and there is market demand in urban SSA for dried sludge as fuel for combustion, protein from insect consumption of sludge and sludge as a soil conditioner for agriculture.[16,17] In rural areas, the most valuable resource is nutrients that can be reapplied to the soil as a soil conditioner to enhance agricultural productivity[18] and biogas for fuel.[19] The majority of faecal sludge characterization and in-depth sanitation market research has been conducted in urban areas.[3] There are few studies that have analysed rural faecal sludge characteristics or looked at appropriate rural faecal sludge treatment technologies. Simple decentralized faecal sludge treatment technologies are the most sustainable options and should be prioritized for rural communities.[20]

For rural Tanzania there is presently no data for the portion of sanitation that is safely managed and only 17.2% of the population has access to basic sanitation services, with the majority of people (63.2%) using unimproved latrines and a high rate of open defecation (15.7%).[21] Faecal sludge characteristics and accumulation rates within latrines vary considerably based on the permeability of the soil, ground water table, number of users, use of toilet paper and quantities of solid waste in the latrine.[22] Faecal sludge is frequently not safely contained within on-site sanitation, however, this is dependent on the hydro-geology.[23] Pit latrines have been demonstrated to contaminate groundwater, withdrawn using wells and pumps, for drinking in Tanzania.[24] In the research area of the Kilombero District, groundwater is the primary drinking water source for 86% of the population, and 48% of people use high-risk open-wells.[25] Despite the high rates of on-site sanitation usage, there is a lack of knowledge regarding; if the faecal sludge is safely contained, to what degree faecal sludge stabilises *in situ*, what are the emptying practices or what type of treatment facilities are needed in rural Tanzania.[26]

The aim of this research was to characterise faecal sludge from pit latrines and develop a treatment system that could be locally operated at a village level in rural Tanzania. This paper reports on faecal sludge characteristics by depth and novel rocket-stove treatment step designed to heat sterilize faecal sludge dewatering leachate (percolate) using agricultural waste-products as the fuel source. The extracted pit-latrine faecal sludge characteristics and the dewatering efficiency of the treatment process are also examined. Finally, the safety of using faecal sludge treated leachate and dried faecal sludge are estimated for unrestricted agriculture use.

## Methods

### Faecal sludge treatment system

The treatment chain consisted of the following steps 1) manual extraction of pit latrine faecal sludge, 2) transportation by three-wheeled motorcycle, 3) solid–liquid separation in three solar drying beds, 4) heat sterilisation of the drying bed leachate in the rocket stove, 5) removal of solids from drying beds, and 6) use of leachate and dried sludge in agriculture. The collection and treatment of faecal sludge from pit latrines took a total of 9 months (February–September), which spanned both wet-season (Feb–May) and dry-season (Jun–Sep). The loading of the system was limited by the drying bed capacity of 0.9–1.35 $m^3$ of raw faecal sludge. The novel aspect of the treatment system was the recovering of faecal sludge leachate from the drying beds for heat treatment. In conventional systems drying beds faecal sludge leachate is normally discharged directly to the ground and valuable nutrients are lost.

### Recruitment of latrines for emptying

In the Kilombero District, the sub-ward of Kining'ina was selected due to its close proximity to the faecal sludge treatment facility. The facility was constructed on land privately owned by Ifakara Health Institute (GPS 8.107368 S, 36.665584 E). The climate is tropical, in 2015 the daily average temperature was 25.6 °C (daily average min 20.8 °C and max 30.3 °C) and a high average annual rainfall of 848 mm (on-site weather station GRWS 100, Campbell Scientific, USA). Through a series of community meetings with the locally elected representatives, households were encouraged to participate in the study as they would receive the benefit of having their pit latrines emptied for free. In total 27 households volunteered to have their latrines emptied.

 

### Faecal sludge collection and characterization

Latrine emptying was staggered between February to September 2015. The number of latrines emptied was a function of the quantity of faecal sludge to be removed, capacity of the treatment plant and numbers of households who agreed to participate. Faecal sludge was manually emptied using hand tools (shovels) and buckets from the pit latrines and transported to the treatment site in sealed 200 L drums in a three-wheeled motorcycle. To avoid direct contact with faecal sludge, trained technicians wore full personal protective equipment (PPE). During faecal sludge emptying, technicians emptied the whole pit latrine while taking a duplicate 100 g of raw faecal sludge random sample at 0.5 m depth intervals during the complete extraction. The pits were extracted in layers, and after each 0.5 m interval the samples were taken, in order to collect data on the different physicochemical and microbiological characteristics of faecal sludge. The faecal sludge samples were cold-chain transported and characterized in the laboratory for pH, conductivity, total solids (TS) (respectively moisture content), total volatile solids (TVS) and faecal indicator bacteria (FIB).

### Drying beds design

Once emptied from pit latrines, faecal sludge underwent solid–liquid separation and drying in the solar drying beds. Drying beds design was adapted from published work[27] and modified to capture leachate from raw faecal sludge (Fig. 1). Drying bed dimensions: length 3.0 m, width 1.5 m and depth 1 m. Drying beds were lined with an initial a layer of coarse gravel (0.1 m), then fine gravel (0.1 m), sand (0.05 m) and a brick layer (0.1 m) laid in a herring bone pattern. The base was constructed with a 15° slanted surface towards the leachate outlet point. Three drying beds were constructed in parallel. Faecal sludge was manually loaded into the drying beds and screened for solid waste. The solid waste was removed and dried. The drying beds were loaded to a depth of between 0.2 to 0.3 m, giving a capacity of each bed of 0.9–1.35 $m^3$ (900–1350 L) of faecal sludge. The faecal sludge from the larger pit latrines exceeded the volume of the drying beds, hence faecal sludge was combined for some latrines to give 24 composite samples. Water was added manually to produce an initial leachate in the first three days (0.1 $m^3$ per day). The sludge was racked and turned by hand daily. The sludge was allowed to solar dehydrate for 21 days, to allow for disinfection of microbial pathogens and to reach a lower moisture content. Faecal sludge leachate was collected from the bottom outlet of the drying beds, using 20 L sealed bucket and further stored into 200 L sealed drums (maximum of 3 days) prior to heat treatment in the rocket stove. Sampling of the faecal sludge in the drying beds occurred after 21 days of activity. Samples were taken in triplicate (100 g each) and analysed for pH, conductivity, TS and FIB. Leachate samples of 100 mL volumes were analysed for pH, conductivity, total suspended solids (TSS), turbidity, TS and FIB.

### Rocket stove design and construction

After collection of faecal sludge leachate from drying beds, the untreated faecal sludge leachate were transferred to rocket stove for heat treatment. A novel rocket stove was designed to treat faecal sludge leachate from drying beds and generate treated leachate fertilizer. The stove design was based on the rocket stove principle mechanism.[28–31] The main components are a firing chamber, top loading feeding system for rice husk (fuel) and air, and a metallic 150 L faecal sludge leachate pot (Fig. 2). Stove dimensions for the chamber consists of ash chamber (20 cm below the slab) and movable grate (19 cm × 29 cm) positioned at 45°. Three air intake chambers were located on the sides of stove; the main air intake chamber (20 cm × 20 cm) was located under the grate, an ash chamber which allowed for removal of ash and a flame window (7 cm × 12 cm) to observe the combustion.

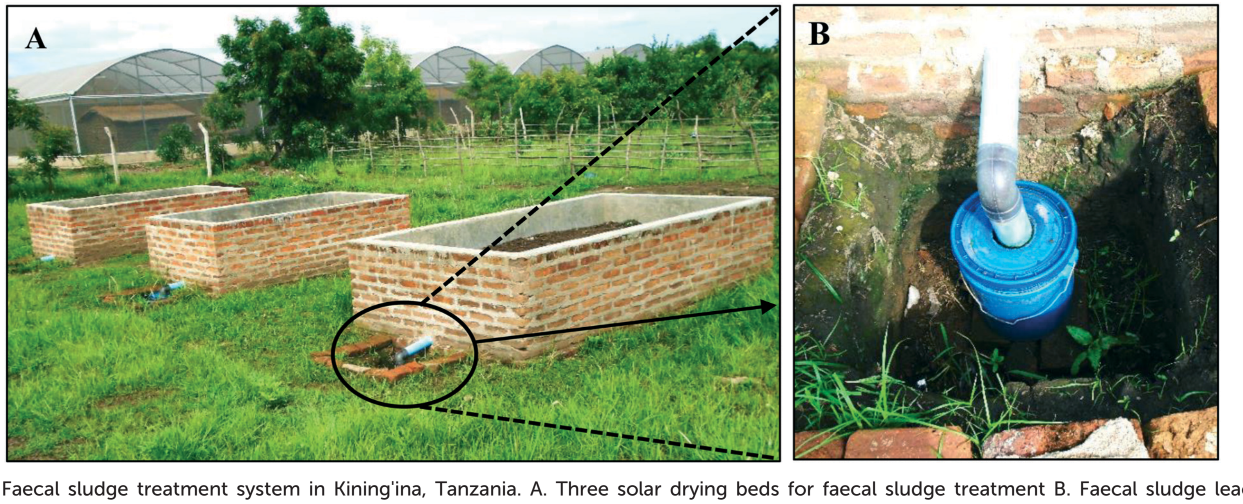


Fig. 1 Faecal sludge treatment system in Kining'ina, Tanzania. A. Three solar drying beds for faecal sludge treatment B. Faecal sludge leachate outlet and 20 L collection bucket.

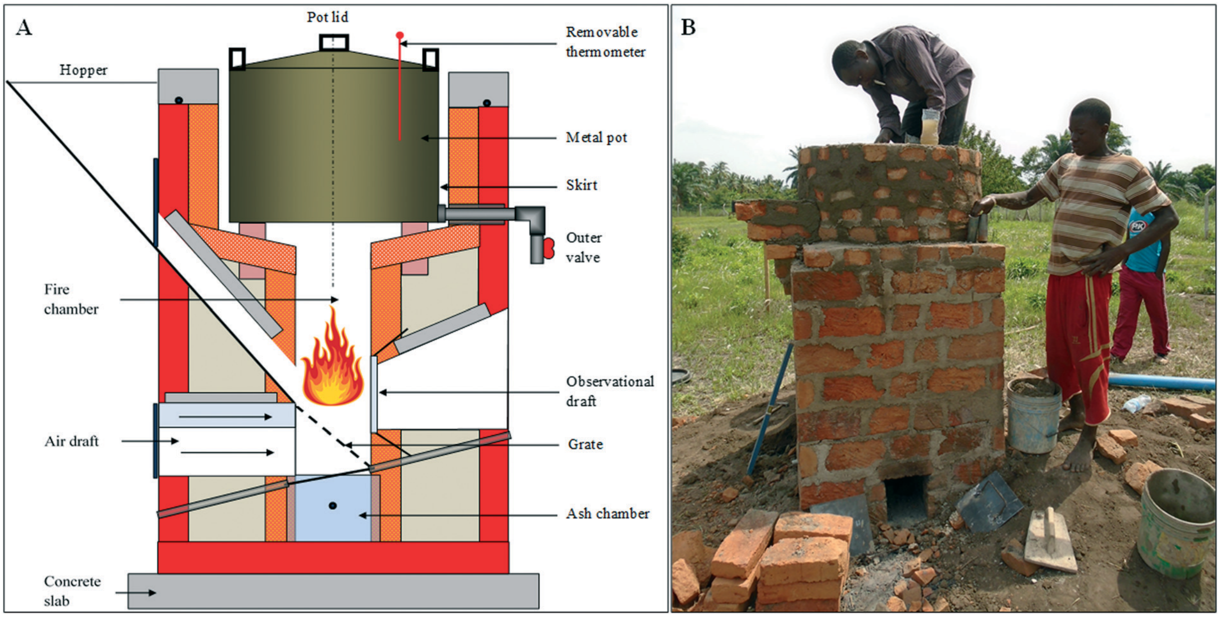


Fig. 2 Rocket stove A. Design schematic. B. Construction using local materials and labor in Kining'ina, Tanzania.



The top loading hopper was angled at 75° to allow rice husk to enter the fire chamber. The metal pot was made from a portion of a used 200 L metal petrol drum (pot volume 1.5 $m^3$). A metal outlet pipe and tap were welded to the drum before construction. Three bricks are firmly positioned to offer support to 1.5 $m^3$ metal pot. An opening between inner wall and the pot (skirt) provided a smooth transition flow of hot gases from the fire chamber to metal pot. The metal pot was top loaded with removable lid and faecal sludge leachate was removed *via* a tap at the bottom of the pot. Stove construction took only two days, using locally available materials and local masons under supervision from an engineer (Fig. 2). The total construction costs were US$ 191 including labor and a small roof over the stove (Table 1).

### Rocket stove operation

The stove relies on rice husk (agriculture waste material) as the main source of combustion fuel. Rice husk was collected freely from nearby consenting households and local rice mills. Rice husk was gravity fed through the hopper at 10 min intervals and retained on the surface of the grate which supports the combustion of the rice husks. To start the combustion process, a small quantity of wood and dried solid waste was used to start a fire at the base of the stove. The changes in temperature (°C) at fire chamber, hopper, skirt and faecal sludge leachate was measured in 10 min interval using a thermometer fitted with K type probe (Acorn® Temp JKT Thermocouple, USA). Heat sterilisation of the faecal sludge leachate took place in a batch-fed mode. To treat faecal sludge leachate, it was heated to approximately 98 °C in the stove and then removed through outlet valve and collected on clean 20 L containers. The performance of the stove was recorded as the time taken to heat sterilize 150 L of the faecal sludge leachate, the amount of heat reaching the metal pot and the quantity of rice husk (kg) consumed per hour. Treated leachate was sampled in 100 mL lots from the outlet tap for pH, conductivity, TSS, turbidity and FIB.

Table 1 Rocket stove constructions costs (US$) in rural Tanzania

| Item | Units | Quantity | US$ per unit | Total (US$) |
|---|---|---|---|---|
| Masons | Days | 4 | 46 | 92 |
| Mortar bricks | Piece | 500 | 0.05 | 25 |
| Cement | Bag | 3 | 6 | 18 |
| Sand | Load | 1 | 9 | 9 |
| Gravel | Load | 1 | 12 | 12 |
| Metal pot | Piece | 1 | 12 | 12 |
| Welding | Days | 1 | 14 | 14 |
| Roof | Piece | 1 | 9 | 9 |
| Total | | | | **$191** |

### Process flow and mass balance

The process flow diagram for the system captures the flow of liquids (water, leachate), faecal sludge and other solids (rice husk and solid waste) (Fig. 3). The system was designed to service households within a 5 km radius to ensure that transportation costs remained low (15 min drive at 20 km $h^{-1}$ in a loaded three-wheeled motorcycle). The mass balances through the treatment system were calculated for one solar drying bed loaded to maximum capacity (1350 L). The mass balances, for both liquids and faecal sludge solids, were estimated based on the conservation of mass[32] and measurements taken through the treatment stages.

 

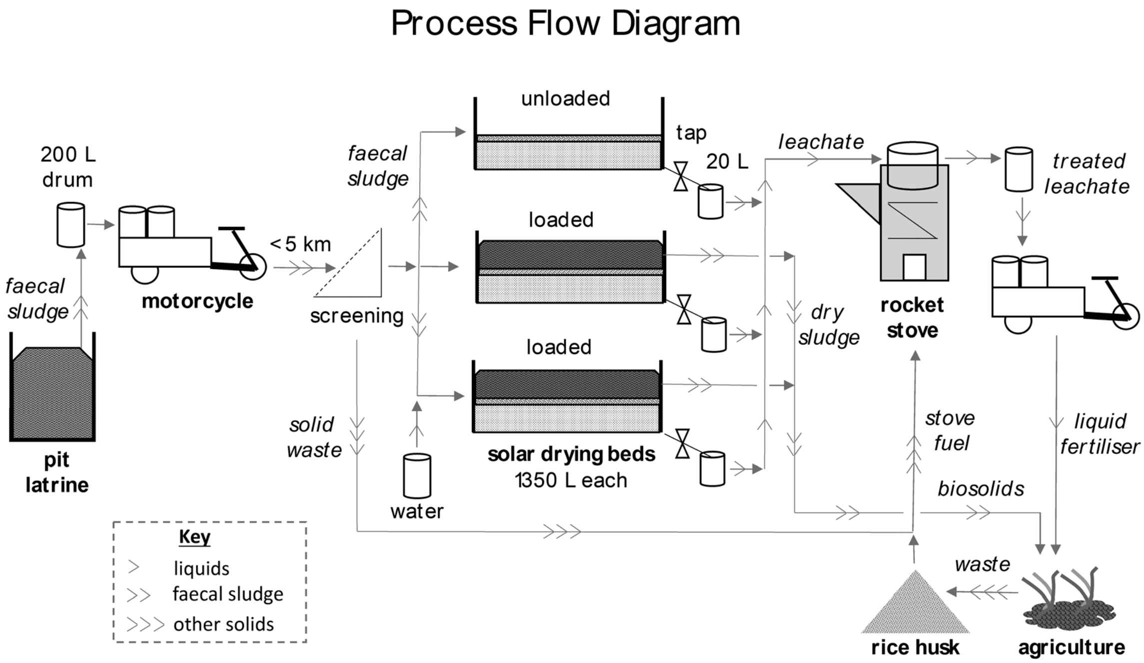


**Fig. 3** Process flow diagram for the faecal sludge treatment system. The flows through the system are separated into: liquids (single arrow), faecal sludge (double arrows) and other solids (triple arrows). The top drying bed is in an unloaded state to indicate how the treatment system was batch operated.

### Sample analysis

Faecal sludge (raw and dried) and faecal sludge leachate (untreated and treated) samples were analysed for physical, chemical and microbiological parameters. To prepare solids samples 1 g of faecal sludge was diluted in a 500 mL of sterile distilled water and blended for 40 s in a standards food blender. For liquid samples, 100 mL of faecal sludge leachate was diluted if required.

For physical tests, pH and electrical conductivity (mS) was measured using a handheld pocket meter (Wagtech, UK) regularly calibrated with standards. Turbidity was measured as nephelometric units (NTU) using a portable turbidity meter (2001Q Hach, USA). Total suspended solids (TSS) were measured in mg $L^{-1}$ using a bench top spectrophotometer (DR 2800, Hach, USA). Total solids (TS) were measured gravimetrically by drying 20 g of solid sample, or 50 mL of liquid, sample in an muffled furnace at 105 °C for 24 h, as per the standard method.[33] Total volatile solids (TVS) were measured by taking the dried TS sample and igniting it at 550 °C for 2 h, as per standard methods.[33]

For microbiology analysis of faecal indicator bacteria (FIB); *Escherichia coli* (EC) and total coliforms (TC) were quantified *via* membrane filtration. Method used was the US EPA 10029 method; briefly 100 mL of prepared sample were filtered through 0.45 μm filters then placed on a membrane pad containing 2 mL of growth media (m-ColiBlue24®, Hach) and incubated at 37 °C (a variation from the method which recommends 35 °C) for 18–24 h. Colonies were counted and recorded as EC and TC colony forming units (cfu) per g of solid or per 100 mL of liquid.

### Data analysis

All data was collated and cleaned in Microsoft Excel (Microsoft, USA), analyzed using R software[34] and graphs were produced using GraphPad Prism© 6.01 (2018, USA). All results were considered statistically significant at a level of $p \leq 0.05$. For physical test data, statistical differences were tested using the parametric test: Welch two sample *t*-test. Differences in pairs of FIB data were tested using the non-parametric tests: Mann Whitney rank sum test.

### Community feedback

On completion, household participants were invited for community feedback sessions and to complete a survey on their willingness to use the products. The summary of project results were shared during the meeting in kiSwahili, and each household was provided with their own results and interpretation. Due to the scope of the project, no toilet upgrades were made. Although, the households were provided with education material explaining alternative latrine designs for safe management of faecal sludge; including urine diversion toilets and low-cost septic tanks.

### Ethics

The research protocol was approved by the Ifakara Health Institute Institution Review Board (approval # IHI/IRB/21_2014) and the Tanzanian National Institute for Medical Research (approval # NIMR/HQ/R.8a/Vol. IX/2055). All households participated in the study voluntarily and signed a participant consent form. On conclusion of the research, results were shared with the relevant stakeholders. Where needed, documents were translated into the local language (Swahili).

## Results and discussion

### Latrine emptying

Of the 27 recruited households, it was found that two of the latrines had collapsed and were not able to be emptied. For all the latrines emptied the faecal sludge was close to the top of the pit. The depth ($d$) dimension of the 25 pit latrines emptied ranged from 0.5 m to <2.0 m. The average depth was 1.07 m and the most common depth was 1 m (22 latrines) (Table 2). The shallows depth of the latrines was likely due to ease of construction and also collapsing of the un-lined latrine walls. The dimensions of the pits surface opening length ($l$) and width ($w$) was estimated at 1 m ($l$) × 1 m ($w$). However, after removing the surface super-structure the pit sides collapsed which made exact measurements difficult. The average capacity of the pits was estimated as 1 $m^3$ of faecal sludge. Calculating the filling rates for the pit-latrines was not within the scope of this study. However, previous research conducting in villages in the same district, found that filling rates in a given year ranged from negative filling to 0.65 $m^3$.[7] The variation between pit-latrines was linked to water quantities present, which had a large impact on the ability to model faecal sludge accumulation rates.[7]

### Raw faecal sludge characterization by depth

The physical and chemical composition of the latrine faecal sludge at 0.5 m intervals, reveals distinct changes. For surface sampling (0 m) in the latrine, fresh faeces and urine were present, while at the depths of 1.5 m faecal sludge had been present for a number of years. The mean pH values were stable at all depths, but the pH decreased from 9.5 at the surface to 8.7 at the bottom. The higher pH (maximum of 9.5) at the surface can be associated with the frequent use of additives such as ashes and lime, to deter flies, reduce odor and faecal sludge content.[35,36] Conductivity reduced considerably from a mean of 79 mS at the surface to 31 mS at 1.5 m depth (Welch $t$-test, $p$ = 0.02). The reduction in conductivity, might be due to leaching of ammonium from urine[37] corresponding to the use of unlined pit latrine. Both pH and conductivity ranges were comparable to values from faecal sludge reported from urban Yaounde, Cameroon (ranges pH 6.5–9.3 and conductivity 15–714 mS).[38]

Total solids (TS) varied slightly across depths and ranged from 38.6–86.8% (Table 2). At the surface (0 m) the average of 56.8% TS was higher than TS values reported (34.0% or 340 g $kg^{-1}$) for pit latrines emptied in communities in the same Kilombero District.[39] However, the comparative study also reported a lower minimum 10.3% (103 g $kg^{-1}$),[39] which could be accounted for by higher rainfall intrusion during the sampling period of the short-wet season (January).[39]

The rural faecal sludge collected had a distinctly higher mean TS (62.7% or 627 g $kg^{-1}$) compared to faecal sludge collected from urban latrines, specifically septage and public toilet sludge in Dakar, Senegal (30 450 mg $L^{-1}$ ∼ 3% w/v)[10] and septage in Bangkok, Thailand (15 350 mg $L^{-1}$ ∼ 1.5% w/v).[40] This difference is attributed to rural unlined pit latrines, where unstable soil sides frequently collapse into the faecal sludge[41,42] combined with leaching of liquid through the side walls of the unlined pit latrine.[17] Resulting in raw faecal sludge with high TS and viscosity, making emptying procedures more difficult[43] and requiring specialist treatment systems.

Total volatile solids (TVS) changed significantly, from a mean of 13.7% (24% of TS) at the surface to only 7.2% (12% of TS) at the lowest level (Welch $t$-test, $p$ = 0.01). The most shallow values were consistent with TVS surface levels reported of 9.8% (28% of TS) for other villages in the Kilombero District.[39] The progressive reduction in TVS quantities at lower depths in the pit latrines indicates the breakdown and stabilisation of faecal sludge. Percentage ratio of TVS/TS was 17.7% over all depths, which is one quarter of urban faecal sludge values reported for public toilet sludge in Accra Ghana of 68% TVS/TS.[44] Higher urban faecal sludge values for TVS are likely due to a range of factors including the younger age of the sludge (<2 weeks).[10] The physical and chemical results highlight the variability of faecal sludge with implications for both extraction and treatment systems.

The densities of FIB (EC and TC) in raw faecal sludge were sampled at 0.5 m interval depths for 21 of the extracted latrines. For both FIB, the densities were highest at the surface for the latrine where there was fresh faeces; with EC mean of 1.1 × $10^5$ cfu $g^{-1}$ and TC mean of 9.5 × $10^5$ cfu $g^{-1}$ (Table 3). There was not a significant reduction in the densities as lower depths with EC densities reduced to a mean of 5.6 × $10^4$ cfu $g^{-1}$ at 1.5 m depths; a reduction of 49% (0.3 $\log_{10}$) (Mann Whitney test, $p$ = 0.33). Similarly, TC decreased to a mean of 9.9 × $10^4$ cfu $g^{-1}$ at 1.5 m depth, a reduction of 90% (1.0 $\log_{10}$) (Mann Whitney test, $p$ = 0.07). These densities are comparable to studies from Kampala, Uganda, where faecal sludge sourced from public toilets and

Table 2 Physical and chemical composition of raw faecal sludge emptied from pit latrines by depth

| Latrine (m) | | pH | | Conductivity (mS) | | TS (%) | | TVS (%) | | TVS/TS (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth | $n$ | Range | Mean | Range | Mean | Range | Mean | Range | Mean | Range | Mean |
| 0.0 | 25 | 6.4–9.5 | 7.9 | 16–504 | 79 | 38.6–86.8 | 56.8 | 5.5–57.1 | 13.7 | 9–66 | 24 |
| 0.5 | 25 | 6.2–9.2 | 7.8 | 6–523 | 58 | 45.7–86.7 | 63.3 | 5.4–16.7 | 9.6 | 7–29 | 16 |
| 1.0 | 22 | 6.3–8.8 | 7.7 | 11–576 | 58 | 45.9–87.5 | 68.8 | 54–12.4 | 7.9 | 7–26 | 13 |
| 1.5 | 6 | 6.4–8.7 | 7.5 | 11–47 | 31 | 52.1–72.3 | 62.8 | 6.7–8.0 | 7.2 | 10–15 | 12 |

 

Table 3 Faecal indicator bacteria (FIB) present in raw faecal sludge emptied from pit latrines by depth

| Latrine (m) | | EC (cfu $g^{-1}$) | | TC (cfu $g^{-1}$) | | EC/TC% |
|---|---|---|---|---|---|---|
| Depth | $n$ | Range | Mean | Range | Mean | Mean |
| 0.0 | 21 | ND[a] – 5.3 × $10^5$ | 1.1 × $10^5$ | 1.5 × $10^3$–3.3 × $10^6$ | 9.5 × $10^5$ | 11 |
| 0.5 | 21 | ND – 3.7 × $10^5$ | 1.1 × $10^5$ | 1.9 × $10^3$–4.7 × $10^6$ | 1.0 × $10^6$ | 11 |
| 1.0 | 19 | ND – 5.5 × $10^4$ | 7.1 × $10^3$ | 4.6 × $10^2$–3.5 × $10^5$ | 7.8 × $10^4$ | 9 |
| 1.5 | 6 | ND – 2.4 × $10^5$ | 5.6 × $10^4$ | 1.6 × $10^3$–4.2 × $10^5$ | 9.9 × $10^4$ | 57 |

[a] ND = not detectable.

septic tanks had TC densities of 1 × $10^5$ cfu/100 mL.[3] Overall, EC densities were on average of 11% of the TC densities for the surface measurements, however this increased to 57% at a depth 1.5 m (Table 3). The increasing portion of EC indicates a changing FIB population, perhaps influenced by a more neutral pH and anaerobic conditions.

There exists a limited quantity of published data on the densities of FIB in faecal sludge, especially from rural latrines. This study highlights that EC and TC densities remain high, even at the bottom of the latrines (1.5 m), where faecal sludge has aged and somewhat stabilised. There exists a known risk to human health due to groundwater contamination from microbial pathogens leaching from pit-latrines.[23] Considering this risk, more research is needed on the growth and persistence of microbiological pathogens in rural pit latrines.

### Faecal sludge treatment in drying beds

After three weeks (21 days) of drying the mean pH and conductivity of the faecal sludge did not change notably (Table 4). However, the TS did increase 1.3 times to a mean of 76.9%, which was significantly higher than raw faecal sludge (Welch $t$-test, $p < 00001$). The percentage range of dried TS was 72.9–85.8%, which was considerably higher than comparable drying beds used for urban faecal sludge in Ghana; which reported a range of 18–49%, after varied lengths of one to 9 weeks of drying.[10] However, the results from this work are similar to the 90% TS achieved after 1.5 to 4 weeks of drying of urban faecal sludge in Dakar, Senegal.[45] The high TS achieved in this study was due to the raw faecal sludge having a higher TS to start with and a treatment system with daily mixing of raw faecal sludge in the drying beds[45] combined with a slanted bed drying surface (15°), which allowed for quicker run-off of faecal sludge leachate.[17]

The drying beds reduced the densities of FIB in faecal sludge. Overall, mean EC decreased by 85% to 1.1 × $10^4$ cfu $g^{-1}$ (ratio 0.15, 0.8 $\log_{10}$ reduction) (Table 4) and indicated a distinct change in FIB population density (Mann Whitney test, $p = 0.04$). The mean was skewed by a few samples with high EC densities, as one-third of samples ($n = 7$) had no detectable EC (Fig. 5), but this was similar to the raw faecal sludge which had nine samples with no detectable EC. The likely explanation for this is that EC is surviving in pockets of treated sludge which have not dried as rapidly. Similarly, the mean TC remained high (2.2 × $10^5$ cfu $g^{-1}$) after drying compared to raw sludge. Hence, the drying process did not consistently reduce the loads of FIB from raw sludge. Faecal sludge drying bed research in the USA has reported that FIB do not reduce in density until a TS > 92% was achieved.[46] Hence, monitoring TS levels and ensuring even drying in the beds will be critical to achieve microbial pathogen inactivation needed to make the use of treated faecal sludge safe in agriculture.

### Rocket stove operation

Leachate captured from the drying beds was heat treated in the rocket stove. A single batch of faecal sludge leachate (~150 L) required an average of 40 min to heat to 98 °C, with maximum temperatures achieved 370 °C for the fire chamber and 250 °C for the skirt area (Fig. 4). To achieve these temperatures 35 kg of rice husk was combusted with a feeding rate of 48 kg $h^{-1}$. Heat around the skirt provided excess heating on the sides of the metal pot and increased faecal sludge leachate temperature. The dips in temperature heating profiles, observed in both skirt and fire chamber

Table 4 Characterization of raw faecal sludge and dried faecal sludge from unlined pit latrines

| | | Raw faecal sludge ($n$ = 25) | | Dry faecal sludge ($n$ = 21) | | Means |
|---|---|---|---|---|---|---|
| Analysis | Units | Range | Mean | Range | Mean | Ratio |
| pH | | 6.2–9.5 | 7.8 | 7.0–8.6 | 7.6 | 0.97 |
| Conductivity | mS | 6.2–576 | 62.7 | 28.2–552 | 87.6 | 1.39 |
| TS | % | 36.8–87.5 | 62.7 | 72.9–85.8 | 79.6 | 1.27 |
| EC | cfu $g^{-1}$ | ND[a] – 5.3 × $10^5$ | 7.3 × $10^4$ | ND – 1.5 × $10^5$ | 1.1 × $10^4$ | 0.15 |
| TC | cfu $g^{-1}$ | 4.6 × $10^2$–4.7 × $10^6$ | 6.3 × $10^5$ | 5.5 × $10^3$–1.1 × $10^6$ | 2.2 × $10^5$ | 0.35 |

[a] ND = not detectable.

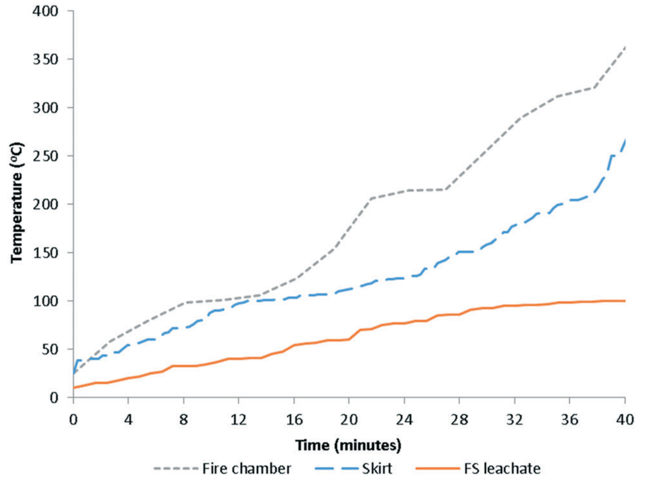


**Fig. 4** Heat sterilisation temperature profiles of faecal sludge leachate using rocket stove fired with agricultural waste.

(Fig. 4), were due to the frequently choking of fire caused by overfeeding of the furnace, blockage of the grate with ashes and excess moisture in the fed rice husk. The operation of the stove was improved by rationing the rice husk feeding and removing ash from the grate.

The amount of heat reaching the metal pot was lower than expected owing to 1) the acute angle of hopper which forced heat upward through the hopper instead of to the pot rest, and 2) excess amount of air-intake through the air draft which diluted the hot gas flowing towards the pot. Heat lost through the hopper after 40 min of heating, when the air-chamber was open was 500 °C and over 300 °C when the air-chamber was closed. The angle of the hopper should be reduced to an angle of 50°, as a design modification for future builds. This would result in a significant amount of heat being re-directed towards the pot and also in-turn lower the stove height by 15 cm, which would aid in ease of operation.

### Faecal sludge leachate heat treatment

The physical and chemical characteristics of the faecal sludge leachate were generally not modified by heat treatment (Table 5). For pH, there was slight increase from a mean pH of 7.76 to 8.95 and mean conductivity increased from 2.52 to 3.13 mS. Leaching of alkali minerals from faecal sludge would have mostly contributed to higher pH in faecal sludge leachate.[42] Raw leachate had an average TSS of 645 mg $L^{-1}$ which is comparable to percolate captured from drying beds in Ghana of 290–600 mg $L^{-1}$.[10] After heat treatment, mean turbidity of the leachate halved from an NTU of 709 to 347, although despite the variability the means were not considerable at the set significance level (Welch *t*-test, $p = 0.8$). A portion of the suspended particles in the leachate were also observed to sediment out during the heating process. The settled sludge had to be removed separately after heat treatment and may present a point of loss of nutrients in the treatment process. Methods to recover this sludge should be built into future stove designs with a drainage point for this sludge.

FIB densities in the raw leachate were high, with mean EC of $3.1 \times 10^5$ cfu/100 mL and TC of $7.7 \times 10^5$ cfu/100 mL, indicating that from the drying faecal sludge in the beds considerable portions of FIB were leaving with the leachate. Data from comparable studies could not be identified and emphasizes the gap this research fills. Heat sterilisation resulted in complete inactivation of EC, from $3.1 \times 10^5$ cfu/100 mL to no detectable organisms ($5.5 \log_{10}$ reduction) (Mann Whitney test, $p = 0.03$). For TC the heat sterilisation removed 99.9% ($3.1 \log_{10}$) reduction leaving just $6.7 \times 10^2$ cfu/100 mL (Mann Whitney test, $p = 0.03$). The heat sterilisation was a significant treatment step in inactivating microbial pathogens. Despite the sterilisation effect of the stove, the safety of faecal sludge leachate would need to be maintained through hygienic handling, storage and during agricultural applications.

### Microbiological safety of treated products

Through the faecal sludge treatment system, the high densities of EC found in raw faecal sludge remained high in some samples of dried faecal sludge and the raw faecal sludge leachate, but were inactivated after the final heat treatment step (Fig. 5). The World Health Organization recommends for safe use of treated faecal sludge and effluent in unrestricted agriculture, EC values $<10^3$ cfu $g^{-1}$ for solids and $<10^3$ cfu/100 ml for liquids.[47] Further, soil transmitted helminth eggs must be not detected at levels of <1/g for solids and <1/L for liquids.[47] In this study, the only samples that were compliant for safe reuse in agriculture was the heat-treated leachate. The dried faecal sludge EC values could be further reduced, by storing the faecal sludge at ambient temperatures tropical temperatures (20–35 °C) for 1 year.[47]

**Table 5** Characteristics of untreated faecal sludge leachate verses treated faecal leachate

| | | Untreated leachate ($n$ = 5) | | Treated leachate ($n$ = 5) | | Means |
|---|---|---|---|---|---|---|
| Analysis | Units | Range | Mean | Range | Mean | Ratio |
| pH | | 7.4–8.2 | 7.76 | 8.3–9.5 | 8.95 | 1.15 |
| Conductivity | mS | 1.5–4.6 | 2.52 | 2–4.4 | 3.13 | 1.24 |
| TSS | mg $l^{-1}$ | 181–1581 | 645 | 376–509 | 450 | 0.70 |
| Turbidity | NTU | 311–987 | 709 | 176–478 | 347 | 0.49 |
| EC | cfu/100 mL | $8.0 \times 10^3$–$6.0 \times 10^5$ | $3.1 \times 10^5$ | ND[a] | ND | $3.2 \times 10^{-6}$ |
| TC | cfu/100 mL | $4.2 \times 10^5$–$1.1 \times 10^6$ | $7.7 \times 10^5$ | 0–$2.1 \times 10^3$ | $6.7 \times 10^2$ | $8.0 \times 10^{-4}$ |

[a] ND = not detectable.

 

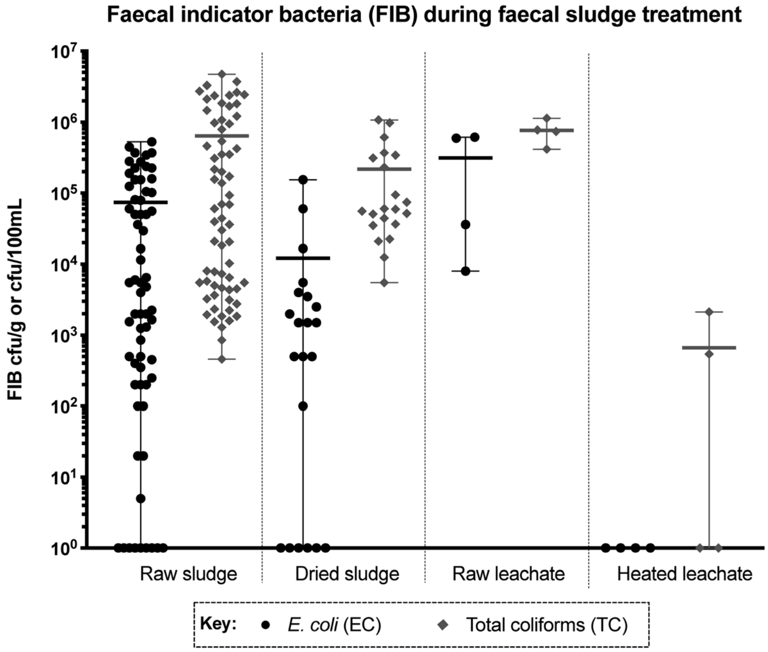


**Fig. 5** Faecal indicator bacteria (FIB) densities, of *E. coli* (EC) and total coliforms (TC) through the faecal sludge treatment system stages. Scatter plot with individual values plotted, black bar represents the mean and whiskers for minimum and maximum values.

Although, there was no analysis of soil transmitted helminth eggs in our treatment system, research in Ghana shows that leachate filtering from drying beds can remove 100% of eggs.[10] Even if there were eggs present in the leachate, the helminth eggs would have been inactivated by rigorous heat treatment. Previous studies indicated significant reduction of helminth eggs when exposed to a temperature range of 50–70 °C,[54–56] while 95 °C temperature treatment ensured complete elimination of helminth eggs.[56] The heat sterilisation step with the rocket stove is a critical treatment stage in producing safe products for use in agriculture.

## Treatment mass balance

The mass balance was calculated based on conservation of mass through the treatment system. For a drying bed loaded at full capacity with screened faecal sludge (1.35 $m^3$), with an average TS of 62.7%, the portions of solids (0.85 $m^3$) and liquid (0.5 $m^3$) were determined (Table 6). Inputs and losses through the system were measured directly and estimated for liquid loss through evaporation. The quantity of solid waste removed prior to sludge loading (Fig. 3) was small (<0.01 $m^3$), hence the solid mass conservation does not include this component. Through the treatment processes solid mass was conserved, while there was a net loss of water (0.42 $m^3$) due to solar evaporation from the drying beds and vapour from the heating leachate. No other studies could be identified in the literature to compare to. This research did not attempt to measuring the mass-balance of organic compounds such as nutrients and chemicals. However, for conventional wastewater treatment plants, research has identified that the majority of chemicals (pharmaceuticals and other personal care products) remain with the bio-solid fraction.[48]

## Faecal sludge treatment system scaling

The loading capacity of the treatment system was limited by the three solar sludge drying beds. Faecal sludge from three

**Table 6** Mass balance calculations for one loaded drying bed at full capacity (1.35 $m^3$)

| Treatment stage | Balance | Material | Raw volume | Factor | Value | Solids | Liquids |
|---|---|---|---|---|---|---|---|
| Loading | Input | Screened sludge | 1.35 $m^3$ | % TS | 62.7% | 0.85 $m^3$ | 0.5 $m^3$ |
| Water addition | Input | Water | 0.1 $m^3$ daily | — | 3 days | — | 0.3 $m^3$ |
| Solar evaporation | Loss | Water vapour | — | — | >21 days | — | (0.4 $m^3$)[a] |
| Leachate capture | Output | Raw leachate | 0.15 $m^3$ | TSS | 0.6% | <0.001$m^3$ | 0.15 $m^3$ |
| Heating | Loss | Water vapour | 0.15 $m^3$ | Boil-off | ~12% v/v[b] | — | (0.02 $m^3$)[a] |
| Collection | Output | Dry sludge | 1.08 $m^3$ | % TS | 79.6% | 0.85 $m^3$ | 0.23 $m^3$ |
| Total input | | | | | | 0.85 $m^3$ | 0.8 $m^3$ |
| Total output | | | | | | 0.85 $m^3$ | 0.38 $m^3$ |
| Total loss | | | | | | — | **0.42 $m^3$** |

[a] Values estimated and not directly measured. [b] Ref. 14.

average sized pit-latrines (1 $m^3$ of faecal sludge) could be emptied and treated per month; an annual treatment loading of 36 household pit-latrines (36 $m^3$ of faecal sludge). In terms of TS, this equates to faecal sludge loading rates range of 1440–2040 kg TS/$m^2$/year. The elevated average TS of the raw faecal sludge (62.7%) in this study, accounts for higher values compared to 67–475 kg TS/$m^2$/year reported previously for septage with TS of <6.5%.[49] Estimating the total community members service was based on filling rates and emptying frequencies. However, the filling rates for rural pit-latrines are challenging to estimate[7] and emptying frequency data was not collected from the community as once full, pit-latrines are normally covered over and abandoned. Hence, estimations for emptying frequency for unlined pit-latrines of an average 8.2 years until the first emptying, were drawn from research conducted in Dar es Salaam, Tanzania.[50] Working of an assumption that pits were constructed at staggered rates across the villages, then the total households the current treatment system could service annually was 295 households (36 pit-latrines by 8.2 years until first emptying). With an average household size of 6 people this equated to 1770 people. To ensure that transportation costs for the rice husk, faecal sludge and products remain low, the plant is only recommended to service households within a 5 km radius (15 min drive at 20 km $h^{-1}$). Further, prior to construction, a feasibility assessment needs to be conducted to determine the availability of appropriate agricultural waste products for the stove (rice husk, corn husk, wheat stalks). For communities with more households within the 5 km radius, the capacity of the plant could be easily increased by building additional sludge drying beds or increasing the surface size of beds. This would be achievable given the low cost of construction and availability of local materials.

To determine the market demand for faecal sludge products a survey of 100 farmers in the in the Kining'ina village to assess their willingness to use and purchase treated faecal sludge. Initial analysis, reveals more than 78% of total respondents were willing to use treated faecal sludge in their agriculture activities and the majority of these were willing to purchase the products in order to replace commercial fertilisers.

The total cost for rocket stove construction was less than US$ 200, this includes the labor hours and materials used as indicated in cost breakdown (Table 1). Construction and maintenance cost for stove were very low compared to other high-end treatment facilities.[51–53] The use of agriculture waste significantly lowered the fuel cost for rocket stove operation, while the main cost incurred was transportation of rice husk to treatment site. The rocket stove design could also be adapted to directly heat sterilise the solid faecal sludge emptied from pit latrines and thus reduce the costs for another treatment stages such as solar drying beds.

### Future research

Future research is needed to understand the treatment processes in greater detail. Also, to ensure safety of the faecal products and to know more about the market requirements. Additional study designs should include enhanced laboratory analysis focus on key nutrients (nitrogen, phosphate and potassium), chemicals of concern (pharmaceuticals – antibiotics) and persistent pathogens (soil transmitted helminths). This would enable a more in-depth understanding of degradation, removal, accumulation and risk profiles for further use. Further, research is recommended to assess the costs effectiveness of mechanisation of the treatment process, by using a small excavator. The markets for the treatment plant products (dried sludge and leachate) needs to be explored further. To assist in determining where this material could increase agricultural productivity, an understanding of the nutrient profiles of both the products and local soil will be required. Further, the economics of what price points small – hold farmers can afford for agricultural products combined with the cost of production will need to be investigated. This research will help determine the long-term scalability and sustainability of the system. Armed with supporting information, policy translation work can commence to transform the regulatory environment, that presently, does not enable innovation in faecal sludge treatment and reuse in Tanzania and more broadly SSA.

## Conclusion

The system enables resource recovery from faecal sludge and provides an alternative to leaving faecal sludge *in situ* or unhygienic faecal sludge disposal directly to the environment. The main significance for this research is the novel adaptation of a rocket-stove to heat treat faecal sludge using agricultural waste products (rice husk). The rocket stove technology is a promising low-cost solution for inclusion in faecal sludge treatments systems in rural SSA. This treatment system also recovers leachate (percolate) as a valuable resource that can be used off-site. Frequently leachate is released on-site into the ground or a French-drain as effluent to grow crops such as bananas. Further research on the market demand for the treated products will inform the scalability of this treatment system. The rocket stove technology can be easily replicated and managed by community entrepreneurial groups to treat faecal sludge from on-site sanitation in rural areas of SSA.

Sustainable and safely managed sanitation requires that rural communities in less-developed countries have access to safe treatment systems. Incentivising safe extraction and treatment through resource recovery is one promising approach that encapsulates both social, economic and environmental drivers. The willingness to use treated faecal sludge in agriculture activities could lead to a sustainable faecal sludge fertilizer business, which could consequently reduce the quantities of untreated faecal sludge entering the environment and improve human health.

## Conflicts of interest

There are no conflicts to declare.

 

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