Characterization and improvement of char quality from pyrolyzed faecal sludge in Dar es Salaam, Tanzania

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Introduction

Resource recovery from faecal sludge (FS) can take many forms, including as a soil conditioner, biogas, black soldier fly protein, building materials, reclaimed water for irrigation, or as a solid fuel. Solid fuel has been shown as an attractive option, particularly in sub-Saharan Africa (Diener *et al.* 2014). In Dar es Salaam, Tanzania, FS currently ends up in the Indian ocean, or is dumped in waste stabilization ponds that are overloaded and treatment objectives are not fulfilled. Resource recovery could be an attractive solution to stimulate proper faecal sludge management (FSM) by generating some recovery of operation costs.

The Sludge to Energy Enterprises in Kampala (SEEK) project initially explored various options for solid fuel recovery from FS, including drying for use in industrial kilns, pelletizing, and slow-pyrolysis. Slow-pyrolysis is the thermochemical treatment of biomass at temperatures between 300-700°C in absence of oxygen, at a heating rate of 1-10°C/min. Slow-pyrolysis can transform dried biomass into a carbonized fuel with a higher energy density (higher heating value (HHV)) than the dried biomass. In this report, the term pyrolysis refers to slow-pyrolysis.

Initial results from SEEK on a laboratory-scale showed potential for slow-pyrolysis of FS (Bleuler 2016). Afterwards, a pilot scale feasibility study of FS pyrolysis was conducted in Dar es Salaam, Tanzania by Hildemar Mendez as part of the WESSP project. The WESSP project (Water and Environmental Sanitation Services for the Poor) focuses (among other topics) on the identification, assessment, documentation and dissemination of human waste resource recovery approaches. During the feasibility study, the design of the pyrolysis reactor was optimized, optimal operation conditions were tested, and experiments were conducted that compared the char characteristics of pyrolyzed FS with that of pyrolyzed paper and pyrolyzed cardboard. Finally, mixed pyrolysis trials with 50% paper or cardboard and 50% FS were done.

The current study was conducted as part of the WESSP project as a student practicum. It follows up on the results of the pilot scale feasibility study.

Research objectives

The goal of this research is to characterize and improve the char quality of slow-pyrolyzed FS, with the following sub-objectives:

1. To compare the char quality of FS from different dewatering technologies available in Dar es Salaam (drying beds with sandy top layer, drying beds with paved top layer, geotubes).
2. To investigate if the quality of FS char can be improved by co-pyrolyzing faecal sludge with other available bio-wastes.
3. To assess the financial and energetic feasibility of producing FS char.

The associated research questions are presented in Table 1.

Table 1: Research questions.

Objective	Research Questions
1. To compare the char quality of FS from different dewatering technologies available in Dar es Salaam (drying beds with sandy top layer, drying beds with paved top layer, geotubes).	• What is the difference in char quality between the pyrolyzed FS obtained from different dewatering technologies? • Could sand in FS char originate from the used dewatering technology?
2. To investigate if the quality of FS char can be improved by co-pyrolyzing faecal sludge with other available bio-wastes.	• What bio-wastes that have potential for co-pyrolysis are available in Dar es Salaam? • What ratio of FS and other bio-wastes yields the best char quality?
3. To assess the financial and energetic feasibility of producing FS char briquettes.	• Could it be financially and energetically feasible to use this char for briquetting?

Materials and methods

This research took place over a period of seven months (January to August 2017) at the University of Dar es Salaam (UDSM), College of Engineering and Technology (CoET) in Dar es Salaam, Tanzania.

Experimental setup

The slow-pyrolysis reactor (Figure 1) consisted of a furnace, a modified oil barrel and a chimney stacked on top of each other. The furnace contained a LPG burner, and a fan to supply secondary air. The barrel contained five rectangular tubes of various sizes with lids and of known weight contained the feedstock (Figure 2). It is the same reactor as used in Zabaleta *et al.* (2016), but with 5 rectangular tubes instead of 7 cylindrical tubes. Three thermocouples (one in the chimney, one inside the middle tube and one on the outer rim inside

Figure 1: The slow-pyrolysis reactor during an experiment.

the reactor) were installed to monitor the temperature profile inside the reactor. Picolog software was used to process the temperature data (i.e. higher heating temperature, pyrolysis time). Oxygen content of the exhaust gasses was measured with a lambda sensor (LambdaCheck) located inside the chimney.

For each pyrolysis experiment, the prepared feedstock was loaded in the tubes, then the tubes were inserted in the barrel, the barrel with tubes was lifted onto the furnace using a crane, and the chimney was fixed on top of the barrel. Gas flow was set to a rate of 6 L/min. Oxygen content was maintained between 2.5 and 3%. Gas supply was switched off once pyrolysis had visibly started by showing combustion of the pyrolysis gasses around the tubes.

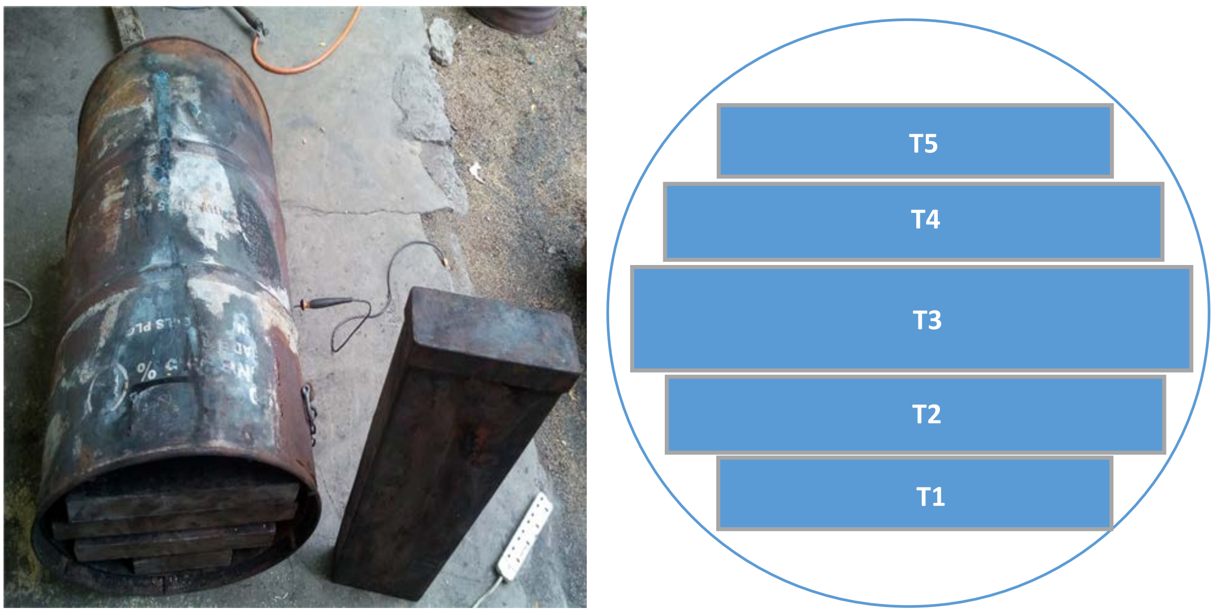


Figure 2: Arrangement of tubes in the barrel

Feedstock

Objective 1: FS from various dewatering technologies

The feedstock for objective 1 came from two different sources and was dewatered in three different dewatering technologies. First, FS dried on sand drying beds was collected at the pilot scale FS treatment plant at UDSM. Faecal sludge from mixed containment origins was brought to the pilot scale FS treatment plant by vacuum truck, and was discharged into the settling-thickening tank. After settling, the thickened sludge at the bottom was pumped to a mixing tank, where it was conditioned with 0.5 mL/g TS chitosan (Biolog-Heppe) before being pumped to unplanted drying beds for dewatering and drying. The FS was dried on the drying beds till approximately 60%TS. Afterwards, any excess sand was brushed from the sludge cakes manually, and the cakes were further dried on a concrete surface in the sun till 90-92%TS.

Second, FS dried on paved drying beds was collected from the FS treatment plant in Kigamboni. The FS treatment plant in Kigamboni consists of a bar screen, a biogas reactor, an anaerobic baffled reactor, unplanted drying beds with a paved layer of porous tiles on the surface and a polishing pond. The dried FS was shoveled off the paved drying beds and transported to UDSM using plastic bags. The sludge was further sun dried on a concrete surface at the UDSM to achieve 90-92%TS.

Third, bench-scale geotubes (63x35cm) from Huesker were used to dewater FS obtained from mixed containment origins that was brought to the pilot scale FS treatment plant at UDSM by vacuum truck. This feedstock was only used for objective 1. On the site of the treatment facility at UDSM, the geotubes were laid out in a crate to capture the effluent, and fed with FS from the mixing tank of the facility (Figure 3). The geotubes were filled with FS to maximum capacity and left to drain for three days before it was taken out of the geotubes and further sun dried on a concrete surface to reach 90-92%TS.

Figure 3: Bench-scale geotube setup

Objective 2: Co-pyrolysis experiments

Softwood sawdust and coffee husks were selected as co-pyrolysis materials based on availability, centralization, competing uses, costs, ash content and HHV of available bio-wastes in Tanzania (Table 2).

Table 2: Selected bio-wastes for co-pyrolysis

Bio-waste	Availability	Competing Uses	Costs	% ash	HHV (MJ/kg)
Sawdust	High	Low	Low	2	18
Coffee husks	High	Low	Medium	1	19

Softwood sawdust was collected from carpentry workshops around the UDSM. The sawdust was sun dried on a plastic surface to 90-92%TS.

Coffee husks (91%TS) were bought from Mbozi Coffee Curing Company in Mlowo town, Songwe region.

FS dried on the UDSM sand drying beds (90%TS) was used for the co-pyrolysis experiments. The larger pieces of dry FS were broken down to small pieces for easy loading into tubes. Mixing of the bio-waste and FS was done manually on a spread plastic bag, before filling the feedstock in the tubes ready for pyrolysis. TS analysis was carried out one day before the pyrolysis day.

Volumetric ratio was used for the co-pyrolysis experiments. To calculate the needed weight of bio-waste and FS for each ratio (i.e. 50:50, 60:40, 75:25 FS:bio-waste), bulk density of the FS and bio-waste were calculated as follows: a tube of known volume **"Z m^3"** was weighed **"W_1 kg"**, then filled with dry FS and weighed again **"W_2 kg"**. The weight of dry FS **"X kg"** was W_2 kg minus W_1 kg. The tube was unloaded, and filled with bio-waste (sawdust or coffee husks) of mass **"Y kg"** (eqn. i and ii). Then the ratio of dry FS to bio-waste (e.g. 60%:40%) was multiplied by the volume of the tube **"Z m^3"** (eqn. iii and iv) in order to know the exact volume occupied by the respective feedstock in the tube. Finally, the volumes according to ratio was multiplied by the bulk density of the material to know the equivalent weight of each feedstock to be filled in the tube according to ratio (eqn. v and vi).

Calculations:

$$Bulk\ density\ of\ dry\ FS = \left(\frac{X}{Z}\right) {kg}/{m^3} \quad \text{.........i}$$

$$Bulk\ density\ of\ bio-waste = \left(\frac{Y}{Z}\right) {kg}/{m^3} \quad \text{.........ii}$$

$$Exact\ volume\ of\ dry\ FS\ in\ tube\ 1 = 60\% \times Z\, m^3 \quad \text{.........iii}$$

$$Exact\ volume\ of\ bio-waste\ in\ tube\ 1 = 40\% \times Z\, m^3 \quad \text{......... iv}$$

$$Equivalent\ weight\ of\ dry\ FS = (ratio \times Z\, m^3) \times ({X}/{Z}\ \frac{kg}{m^3}) \quad \text{.........v}$$

$$Equivalent\ weight\ of\ bio-waste = (ratio \times Z\, m^3) \times ({Y}/{Z}\ \frac{kg}{m^3}) \quad \text{.........vi}$$

In order to obtain the equivalent weights of the feedstocks (amounts) to be mixed in the respective tubes, the ratio was multiplied by the mass of the feedstock when full in the tube.

$$Equivalent\ weight\ of\ dry\ FS = 60\% \times X\ kg$$

$$Equivalent\ weight\ of\ biowaste = 40\% \times Y\ kg$$

Laboratory analysis

Total solids (TS) and proximate analysis (% volatile solids, % ash and % fixed carbon) were carried out in triplicate for all samples, according to standard methods (ASTM 2007, 2013, 2015). Values for % fixed carbon and higher heating value (HHV) were calculated from empirical formulas (Parikh *et al.* 2005). Char yield was calculated with the following equation:

$$Char\ yield\ (\%) = \left(\frac{Char\ weight\ (kg)}{Dry\ feedstock\ weight\ (kg)}\right) \times 100$$

Sand content was analyzed according to German Association for Water Wastewater and Waste (2008) guidelines, using a 0.1M HCl solution.

Financial feasibility analysis

An estimation of financial feasibility of fabricating FS char briquettes was made by comparing the production costs (material and operation costs) with the revenue expected. Revenue was estimated by a small willingness-to-pay user survey with four potential customers. A first batch of FS char briquettes with 50% FS and 50% sawdust char (Figure 4 left) was produced using the Peyam Screw Press (Figure 4 right), and the briquettes were distributed to four restaurants around Ubungo in Dar es Salaam. Feedback was collected with a user survey. Then, a second batch of FS char briquettes with 50% FS and 50% sawdust char was produced, distributed to the same customers and comparative feedback was recorded.

Figure 4: FS char briquettes (left), and Peyam Screw Press machine for making briquettes (right).

Energy efficiency

To determine energy efficiency of char production, net energy balance (Q_{net}) was calculated. The drying energy (Q_{drying}) was neglected, since the dry FS was sun dried and no external energy was supplied. Thus, the net energy balance was calculated as:

$$Q_{net}(MJ) = Q_{yield}(MJ) - Q_{pyrolysis}(MJ)$$

Whereby:

$Q_{yield}(MJ) = Char\ yield\ (kg) \times HHV_{char}\ (MJ/kg)$

$Q_{pyrolysis}(MJ) = LPG\ consumption\ (kg) \times HHV\ of\ LPG\ gas\ (MJ/kg)$

Results and Discussion

Reactor operation

During the pyrolysis process three phases were observed. First is the drying process, whereby the moisture was being driven off by heat, during this phase a grey smoke was observed with a gradual increase in temperature in the middle tube. Second was the pyrolysis phase, whereby flames were observed coming out from the tube lids, indicating that moisture had evaporated and the volatile solids were volatilizing. During this phase the temperature in the reactor rose rapidly to the maximum temperature. The last phase is the cooling off phase, where the temperature gradually dropped.

Figure 5: Observation of pyrolysis flame with a mirror.

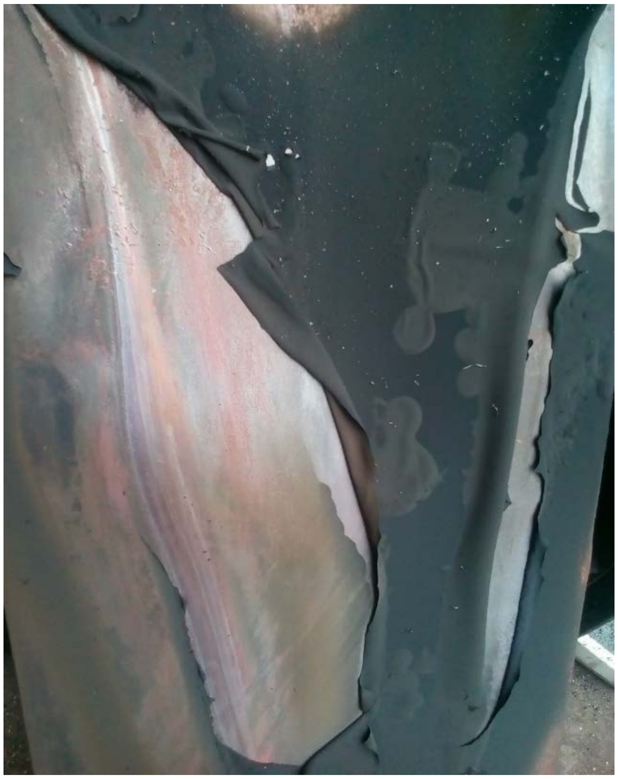


Figure 6: A close-up of the outside of a tube with a layer of soot on it.

During all pyrolysis experiments the middle tube (T3 in Figure 2) was observed to be the first one to start pyrolysis, followed by T4 and T5. For some experiments which the pyrolysis time was shorted after observing intensive pyrolysis flame from the T3, two tubes (T1 and T2) weren't fully carbonized. Therefore, LPG should only be switched off after observation of pyrolysis flame from all the tubes using a glass mirror (Figure 5).

Incomplete combustion was noticed at several occasions by the layer of soot coating the side walls of the tubes after pyrolysis (Figure 6). Reasons for that could be 1) Low temperature, 2) Insufficient mixing of fuel and sufficient air (turbulence), 3) Not enough time for the combustion. Since point 1 and 3 were ensured, it was suspected that the amount of secondary air supplied was insufficient. The situation was especially critical for the experiments with a high ratio of FS, particularly for the experiments with 75% FS and 25% coffee husks. Even after the application of an additional fan, no significant change was observed. In future experiments, a stronger fan needs to be used to ensure adequate turbulence with high ratios of FS.

Objective 1: FS from various dewatering technologies

Best char quality was defined as the char with the highest HHV and the lowest ash content. The average results for the char yield, ash content and the HHV for the FS from different containments origins, reveal that the char from geotubes had the highest char quality (Figure 7). It has a HHV of 8 MJ/kg, while sand drying beds and paving tiles had a HHV of 6 MJ/kg and 5 MJ/kg, respectively. Char from geotubes also has the lowest ash content of 67%, compared to the sand drying beds and the paving tiles with an ash content of 73% and 77%, respectively. The char yields are similar for the three samples (59%, 53% and 58% for the sand drying beds, paving tiles and the geotubes, respectively). The sludge from the paving tiles was digested in an anaerobic digester during treatment, that is likely why the HHV of those samples are the lowest.

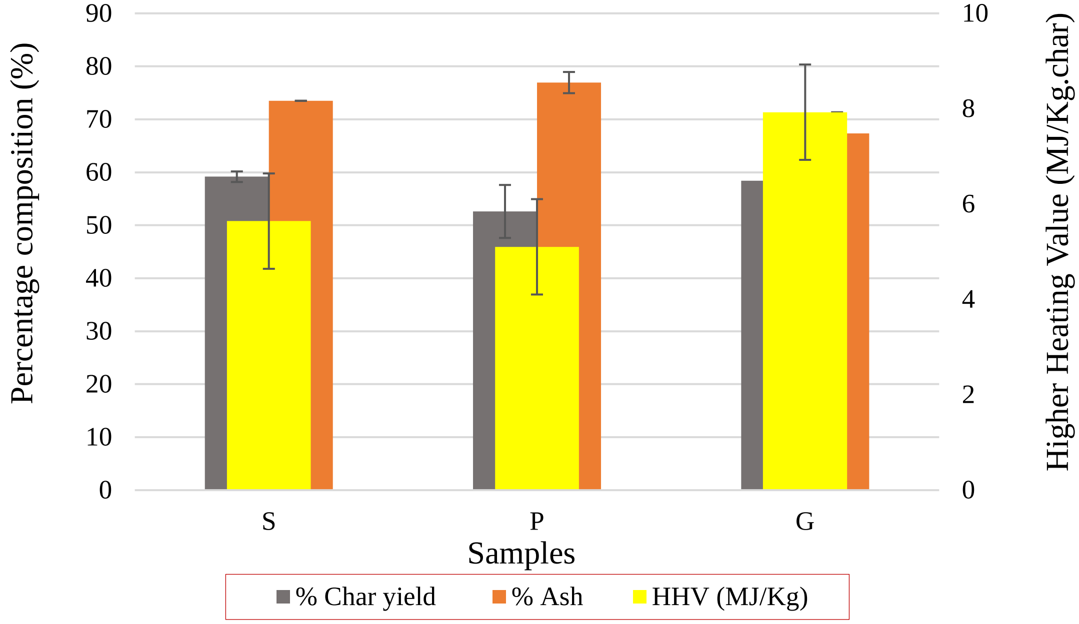
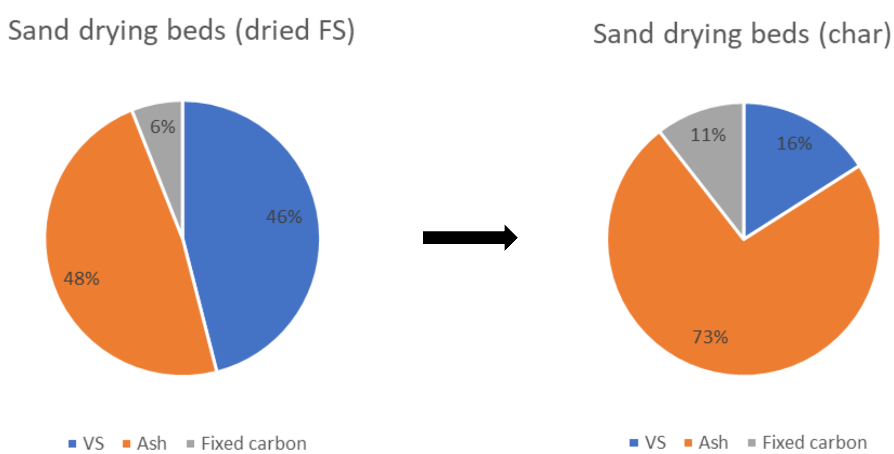


Figure 7: FS char characteristics from different dewatering technologies (S = sand drying beds, P = paving tiles and G = geotubes).

The HHV of the dried sludge before pyrolysis was on average 9 MJ/kg for sand drying beds, 5 MJ/kg for paving tiles, and 11 MJ/kg for geotubes. The FS from the paving tiles was digested in an anaerobic digester during treatment, which could be a reason why the HHV is lowest. Pyrolysis did not improve the energy density of FS. A comparison of proximate analysis shows the effect on composition that the carbonization had on the FS product (Figure 8). The same trend can be observed across all samples, where the ash content and fixed carbon content increased, and the volatile solids decreased. The geotube FS had the lowest ash content both in dry FS and char.



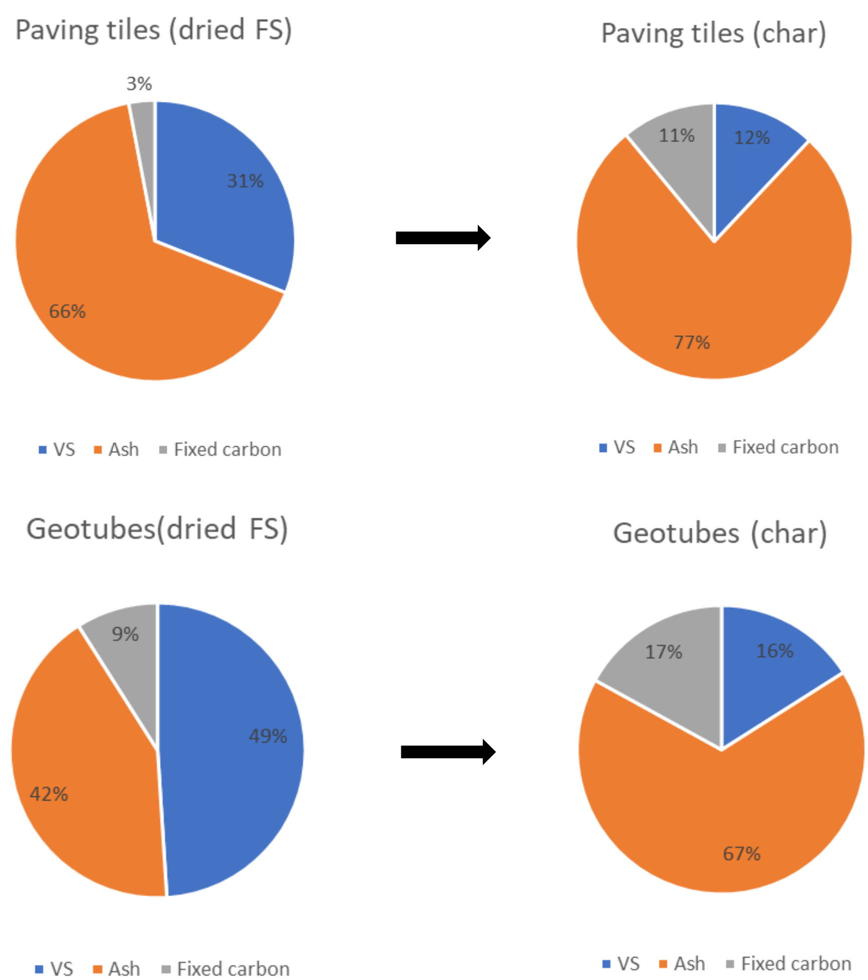


Figure 8: Proximate analysis of the dried FS feedstock versus the pyrolyzed char.

The average sand content in the ash fraction was 77% for the sand drying beds, and 72% for the geotubes. This corresponds to 57% and 49% of the total char mass. Char from the geotubes had 14% less sand than the char from the sand drying beds.

Objective 2: Co-pyrolysis

Co-pyrolysis of FS with sawdust improved the efficiency of the pyrolysis experiments by reducing the amount of LPG consumed. The time to start pyrolysis (observed pyrolysis flame), increased as the ratio of dry faecal sludge increased in the ratio. The average time for starting pyrolysis was 20 minutes, 24 minutes and 47 minutes, for the samples with 50%, 60% and 75% FS respectively. This implies that the FS consumes more LPG during pyrolysis than the sawdust. An explanation for this could be the reduced air turbulence in experiments with a higher FS ratio, as observed earlier in this report (see paragraph Reactor operation). A fundamental future research question for FS pyrolysis could be to understand what properties contribute to why FS takes longer to start pyrolysis.

As the ratio of the dry FS increased in the co-pyrolysis with either the sawdust or coffee husks, the quality of the char reduced. The 50:50 ratio yielded char of best quality for both feedstocks. The increase in fraction of FS raised the ash content, and lowered the HHV (Figure 9 & Figure 10).

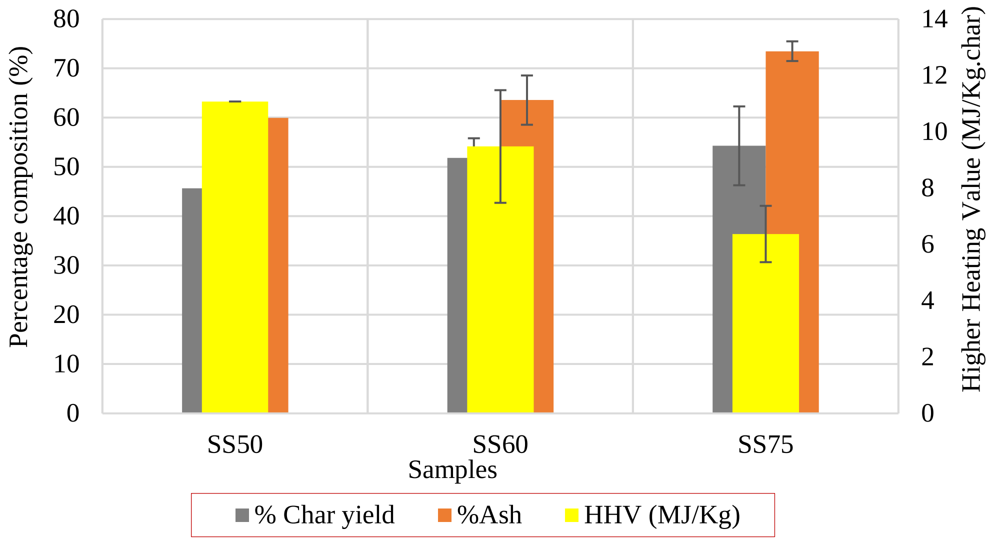


Figure 9: Characteristics of char from samples with ratios of 50:50 FS:sawdust (SS50), 60:40 FS:sawdust (SS60), and 75:25 FS:sawdust (SS75).

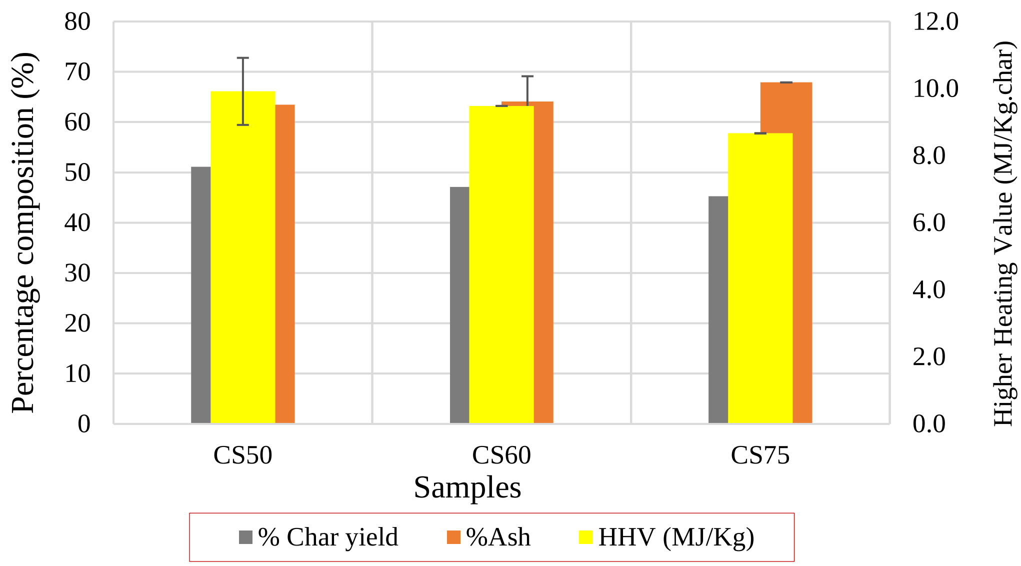


Figure 10: Characteristics of char from samples with ratios of 50:50 FS:coffee husks (CS50), 60:40 FS:coffee husks (CS60), and 75:25 FS:coffee husks (CS75).

Table 3 shows a comparison between co-pyrolyzed FS char and commonly used biomass chars in Dar es Salaam. The ash content of the FS char is much higher than that of any other available char source, which makes it unattractive. HHV is also lower than the alternative sources.

Table 3: Difference in ash content and HHV between FS char (50:50 FS:sawdust) and other locally used solid fuel sources.

Energy Source	**Ash Content**	**HHV (MJ/Kg)**
FS char	60	11
Charcoal	8	29
Char briquettes (Arti Energy)	35	19
Char briquettes (Mkaa poa)	30	21

Objective 3: Feasibility of FS char production

Energy efficiency

The average required LPG input for one co-pyrolysis experiment of 50% FS and 50% sawdust was 200L. Net energy per experiment of the 50:50 FS:sawdust was 85.8 MJ.

$$Q_{net}(MJ) = Q_{yield}(MJ) - Q_{Pyrolysis}(MJ)$$

$$Q_{net}(MJ) = \frac{11MJ}{kg} * 11.14kg - 49\frac{MJ}{kg} * 0.75kg$$

$$Q_{net}(MJ) = 85.8\ MJ$$

The net energy was not calculated for 50:50 FS:coffee husks.

Financial feasibility

The average willingness-to-pay price between the four restaurants in Dar es Salaam was 1300TSh/kg. A cost comparison between the FS char briquettes and other locally applied cooking energy sources (Table 4) shows that the FS briquettes could be sold for a slightly lower price than alternative cooking energy sources. The lower price could make them favored by low income consumers.

Table 4: Cost comparison between the FS char briquettes and other energy sources

Energy Source	FS char briquettes	Charcoal	Mkaa Poa	Briquettes (Arti Energy)
Cost per kg	1,300	2,000	1,500	2,000

The investment costs are summarized in Table 5. The cost for the installation of the pyrolysis reactor and that of the briquette machine (PSP) are the highest investment costs, while the rest falls under operation cost. The costs for manpower are not included in Table 5, since the calculations are made for this small-scale phase only.

Table 5: Investment costs for the FS briquettes (12kg).

	Material	**Quantity**	**Cost (TSh)**
1	Saw Dust	7.17 Kg	0 (Free)
	Transportation	7.17 Kg	1,000
2	Dry FS	17.22 Kg	0 (Free)
3	Pyrolysis Reactor	1 system	2,000,000
4	Waste Paper	3 Kg	0 (Free)
5	Water	40 liters	400
6	Briquette Machine "PSP"	1 unit	1,200,000
Total Cost			**3,201,400**

One FS char from one pyrolysis experiment produces up to 12 kg of dry briquettes, which brings 15,600 TSh after being sold at an average cost of 1,300 TSh/kg. By daily production and selling of the briquettes, and assuming that sun is used for drying, the investment cost could be paid back after 205 working days ($3{,}201{,}400/15{,}600$).

Conclusion and recommendations

Conclusions

- The slow-pyrolysis reactor was relatively simple to operate for trained staff. After ignition of the LPG flame, only two openings (chimney and at the furnace) need to be managed during the pyrolysis reaction. A reactor as used in this report is suitable for situations in which a simple, locally available, and relatively inexpensive reactor is required, such as in low-income settings.
- During operation, large amounts of soot indicated that there was not enough mixing of air to fuel the combustion of pyrolysis gases. A secondary air source is needed in this type of reactor for high ratios of FS. Future research could focus on understanding the properties of FS that contribute to this decreased turbulence in the reactor.
- On average, the FS char in Dar es Salaam had a low HHV, ranging between 5-9 MJ/kg. Compared to dry FS, pyrolysis did not improve the HHV in this study. Therefore, using dried FS for direct combustion could be considered as an option in situations where that is appropriate.

- The energy content of the FS char is improved through co-pyrolysis with other bio-wastes. 50:50 FS:bio-waste yielded the best char quality, with a HHV of 11 MJ/kg and an ash content of 46% for 50:50 FS:saw dust, and a HHV of 10 MJ/kg and an ash content of 51% for 50:50 FS:coffee husks.
- FS treated in an anaerobic digester had a lower HHV than FS that was not treated in an anaerobic digester. Char from anaerobically treated FS was also lower in calorific value than not anaerobically treated FS char.
- Sand content in the dry FS reduces the quality of the sludge. 12% of sand in FS char originated from the sand drying beds.
- FS briquettes from FS and sawdust (50:50) were received positively by potential customers in Dar es Salaam. A comparison of the FS char briquettes with other locally available cooking energy sources showed that the FS briquettes were much lower in HHV and much higher in ash. However, this hardly affected customer perception and satisfaction. Establishing a small-scale FS briquettes production company requires at least an investment cost of 3,201,400 TSh. Return period was estimated at 205 working days of daily operation.

Recommendations

Future research could look into the difference in char quality from FS from different containments origins (e.g. lined pits, unlined pits, septic tanks, etc.). Sand from containments increases the ash content in FS. Different containment technologies might have different contributions to the sand content in FS. In addition, more fundamental research could focus on understanding the properties of FS that result in reduced mixing of air during FS pyrolysis.

Many industries in Dar es Salaam need heating energy. This study showed that pyrolyzed FS has a lower energy content than dried FS. Before deciding for pyrolysis, it is worth investigating whether that is most appropriate. At a large scale, dried FS could be used directly as a fuel, for example in the cement industry. However, dried FS still contains pathogens and is therefore less suitable for household use. It is recommended that some effort could be made to convince and sensitize industries in Dar es Salaam to consider FS fuel.

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