SLOW PYROLYSIS OF URBAN BIOWASTE IN TANZANIA – AN ANALYSIS OF THE TECHNICAL AND SOCIO-ECONOMIC POTENTIAL

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ABSTRACT: Many households in many low and middle income settings have difficulties in finding affordable, reliable and sustainable cooking fuel. Charcoal, solid fuel resulting from carbonizing wood biomass, is still the main fuel consumed by over 90% of households in Dar es Salaam, Tanzania. This puts increasing pressure on the national woodlands. Char production is however not necessarily only limited to wood as raw material. Suitability of currently unutilized biowaste for char-dust production and briquetting was tested with a experimental unit in Dar es Salaam. First experiments with cardboard waste showed favorable energy ratios and high heating values (HHV) of 21.6 – 24.3 MJ/kg_{db}, similar to those of bituminous coal. In addition, a stakeholder assessment and analysis was conducted to identify potentially suitable entrepreneurs for a biowaste-to-char-dust start-up enterprise using a developed set of criteria. Results show that enterprises already in char-briquetting business or providing waste collection services were the two stakeholder clusters that scored highest with regard to their suitability. Access to sufficient space to set up a char making facility shows to be the main bottleneck for all stakeholders. An assessment of the enabling environment identified five core issues that hinder the development of a waste to char market (i) customer preference towards wood-based charcoal, (ii) lack of fiscal empowerment in the charcoal sector, (iii) lack of legal empowerment in the charcoal sector, (iv) low capacity of authorities for policy implementation and enforcement and (v) fragmentation of institutional responsibilities.

KEYWORDS: Carbonization, slow pyrolysis, energy recovery, biowaste, organic solid waste, multi-criteria analysis

Proceedings Venice2016, Sixth International Symposium on Energy from Biomass and Waste, 14 - 17 November 2016
Great School of St. John the Evangelist, Venice, Italy

1. INTRODUCTION

The provision of affordable, reliable and sustainable cooking fuel for urban residents in many low- and middle-income settings is still a major challenge (Maes and Verbist, 2012). Charcoal, a solid fuel resulting from carbonization of wood biomass in the absence of air at a temperature above 300°C, is the main cooking fuel for millions of households in urban and peri-urban Sub-Saharan Africa (SSA; IEA, 2009). In Dar es Salaam (DSM), Tanzania, the proportion of households using charcoal rose from 47% in 2001 to 71% in 2007 and has reached 94% in 2011 (World Bank, 2009). This is most likely driven by high population and urban growth (WEO, 2010; Arnold et al., 2006; Zulu and Richarson, 2013). Currently, over 500'000 tons of charcoal are consumed yearly. Most of this charcoal derives from unsustainable sources of wood biomass and is produced using traditional earth-mound kilns with char yields around 10 – 15% (Bhattacharya et al., 2002; Antal and Grønli, 2003; Sebokah, 2009). Such charcoal production is causing severe pressure on local forest stocks and an estimated forest area loss of 7% in the last 25 years is attributed to charcoal production (World Bank, undated; Mwampamba, 2007).

Char production however does not necessarily need to be limited to wood only. Also organic solid wastes generated in agriculture and even urban environments can be carbonized (Lohri 2015a). The obtained char-dust can be further processed into char-briquettes which can then be used as cooking fuel (Vest, 2003; Mwampamba et al., 2013). Several Community Based Enterprises (CBE) already exist in DSM which produce char-briquettes derived from carbonized agricultural wastes. Amounts produced from agricultural wastes are difficult to estimate but are far smaller than the wood-based charcoal supply (Lohri et al., 2015b). Urban biowaste, currently unutilized and often discarded hereby impacting severely on the environment, represents a potential alternative feedstock for char production. Urban biowaste-based briquettes could increase the supply of sustainable fuel alternatives and at the same time help improve the poor solid waste management situation in DSM. Urban waste management in DSM is characterized by a high fraction of organic matter (~60%), low waste collection rates (<40%) and lack of treatment and inappropriate disposal such as open burning, uncontrolled burying and dumping (Breeze, 2012). In spite of the unexploited potential, of urban biowaste-based briquettes, there is still limited research available on practical decentralized carbonization solutions for different types of municipal organic solid waste which could be applied in low-income settings (Lohri et al., 2015a).

The research presented in this paper is one outcome of a collaboration project between the University of Dar es Salaam and the Swiss Federal Institute of Aquatic Science and Technology (Eawag). The aim was to explore the suitability of urban biowaste as feedstock and test a locally designed and built reactor using slow pyrolysis to produce char-dust from waste. A first phase of the project attested a small-scale experimental pyrolysis unit which consisted of a closed standard oil drum (208 L) inserted horizontally into a brick kiln (Figure 1) and heated with an external fuel source. The required heat was supplied by combusting liquefied petroleum gas (LPG). Three biowaste types (packaging grass (PG), wood waste (WW) and cardboard waste (CB)) were carbonized in this reactor. Results of the produced char showed promising char yields (PG: 38.7%; WW: 36.2%; CB: 35.7% on dry basis), proximate composition (volatile carbon, fixed carbon and ash content) and heating values (PG: 20.1 MJ/kg; WW: 29.4 MJ/kg; CB: 26.7 MJ/kg) which compared well with literature data (Lohri et al., 2015a). However the energy content of the char generated was not able to surpass the energy applied in form of LPG to obtain the char. The average ratio between these two parameters, measured as Energy Ratio (ER), was 0.49 ± 0.11 (Rohr, 2015).

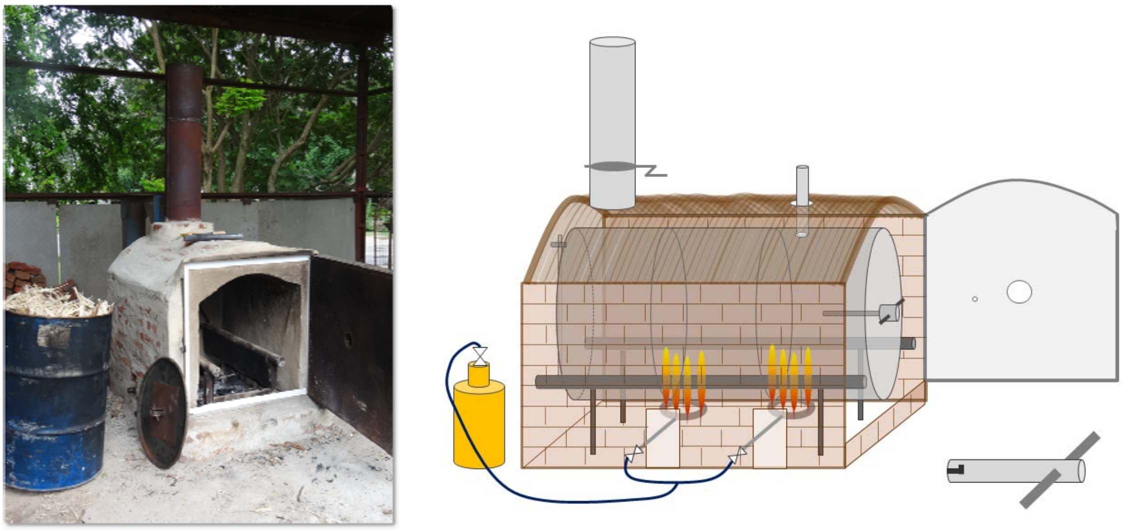

Figure 1: Photo and schematic of first experimental slow pyrolysis unit (Lohri et al., 2015a).

A second phase of the project then aimed at building and testing a new small scale experimental reactor to improve the energy efficiency and obtain a positive energy balance. The second objective of this phase also involved conducting a stakeholder assessment and analysis to identify potentially suitable entrepreneurs for a biowaste-to-char-dust start-up enterprise based on a developed set of criteria as well as assessing the enabling environment that fosters or hinders char-dust production in Dar es Salaam.

2. MATERIAL AND METHODS

2.1. Technical system

The experimental pyrolysis unit had to match several criteria, namely low production costs, local availability of materials, ease of construction and operation, simple maintenance and repair, easy control of the carbonization process, simple measurement of supplied energy, safety, and ergonomics for use by one worker.

The technical solution designed and constructed at the University of Dar es Salaam (UDSM) is a low-cost and semi-continuous slow pyrolysis reactor-system. Its design was based on a different concept to the first unit (Bühler and Schmidt, 2011). It includes a bottom furnace, two vertical standing oil-barrels (208 L) and an exhaust chimney. All these elements are stacked on top of each other (Figure 2). A crane system was added to move and stack these components.

Figure 2: Photo and schematic of experimental unit.

Each barrel contains a cylinder with same height but slightly smaller diameter than the barrel. This cylinder is centered and welded to the barrel, leaving a gap of 6 cm between the barrel and the cylinder wall (Figure 3). This gap is filled with glass wool, as insulating material. The cylinder contains seven metallic pipes with a diameter of 15 cm each, a volume of 14.5 L each and sealed at one end. Feedstock for carbonization is inserted into these pipes which are then closed with a metal lid. The total feedstock volume of all pipes together is 101.5 L, almost half of the total barrel volume. The remaining space between the pipes is left empty and enables the upward draft towards the chimney.

Figure 3: Close-up of the open barrel, the slightly smaller cylinder and the 7 pipes in the cylinder.

As shown in Figure 2, the system is set up with two barrels on top of each other. The feedstock in the bottom barrel is carbonized while the waste heat is drafted upwards to heat, and if required, to dry feedstock contained in the upper barrel. In this experimental set up the furnace, is fueled by LPG which has a high heating value (HHV) of 50 MJ/kg. This was necessary to ensure better heat control and more constant heat supply. Ideally the furnace could also be fueled with biogas from an anaerobic digester or even with landfill gas. Pyrolysis gas is generated inside the pipes during the carbonization process. This gas finds its way through the lids of the pipes as these do not seal hermetically and then combusts when in contact with oxygen. This provides extra heat to the process, and helps reduce the LPG consumption.

2.1.1. *Feedstock*

Corrugated cardboard waste, which was supplied by a waste collection & recycling company, was used as feedstock for the carbonization experiments. The feedstock was selected as it is quite uniform with constant properties, has a low moisture content and can easily be stored. The cardboard was shredded into off-cuts of approximately 5 x 5 cm. Impurities such as plastics and adhesive tape were removed manually before inserting the material into the reactor.

2.1.2. *Experiments and analysis*

The cylinders were filled with shredded corrugated cardboard waste. Total mass of cardboard waste inserted per barrel and experiment was 7.99 kg_{db} (db = dry basis).Three preliminary experiments were conducted with only the lower barrel (Series 1) and two experiments with both barrels (Series 2). Temperature inside the bottom barrel (at the base of one of the pipes) was continuously recorded using a thermocouple. The end of the experiments was determined by the moment when no more pyrolysis gas was generated and the LPG supplied was turned off.

Composition of feedstock and char were determined using proximate analysis methods. Moisture content (MC%) was determined by measuring the percent weight loss after the samples were dried at 105°C as indicated in BS EN 1477 - 3:2009 standard test method for solid biofuels. The volatile content (VC%) was determined by measuring the percent weight loss of the dried samples after heating for 7 min at approximately 950°C, as indicated in ASTM E872-82 standard test method. The ash content (ASH%) was measured by the percent weight loss after burning the dried samples in a muffle furnace at 575°C according to ASTM E1755-01. Fixed carbon (FC%) was calculated by the sum of ash and volatile matter percentage and its difference to 100%. Char yield (y_{char}) was calculated on dry basis:

$$y_{char} = m_{char,\ db}/m_{feedstock,\ db} \qquad \text{Equation 1}$$

where $m_{char,db}$ is the mass of the generated char (dry basis) and $m_{feedstock,db}$ is the mass of the original feedstock (dry basis). The fixed-carbon yield (y_{FC}), which is an indicator of carbon efficiency, was calculated according to:

$$y_{FC} = y_{char} \cdot [FC\%_{char} / (100 - ASH\%_{feedstock})] \qquad \text{Equation 2}$$

where $\%FC_{char}$ is the fixed carbon content of char in percent and dry basis and $\%ASH_{feedstock}$ is the percentage ash content in the feedstock on dry basis (Antal et al., 2000). In addition, the higher heating values (HHV) of the chars were determined using an empirical calculation based on proximate analysis (Parikh et al., 2005).

$$HHV = 0\ 3536 \cdot FC\%_{db} + 0\ 1559 \cdot VC\%_{db} - 0\ 0078 \cdot ASH\%_{db} \qquad \text{Equation 3}$$

2.1.3. *Energy calculations*

The Energy ratio (ER) is the relation between the energy of the resulting char (mass of char multiplied by its HHV) and the energy consumed to make the char.

$$ER = [m_{char,\ db} \cdot HHV_{char,\ db}] \,/\, [m_{LPG} \cdot HHV_{LPG}] \qquad \text{Equation 4}$$

where $HHV_{char,\ db}$ is the high heating value of the char (dry basis), HHV is the high heating value of LPG (50 MJ/kg) and m_{LPG} is the mass of consumed LPG. Energy consumption was measured by weighing the LPG cylinder before and after use and multiplying this by a HHV of 50 MJ/kg for LPG.

2.2. Stakeholder analysis and assessment

2.2.1. Identifying the stakeholders

Those involved in the charcoal or char-briquette producing businesses were targeted, as these were assumed to have the highest potential to engage in a biowaste-to-char-dust business. A preliminary list of stakeholders was elaborated based on interviews with two organizations knowledgeable of the waste management and/or char sector in Dar es Salaam. BORDA TZ is specialized on sanitation and solid waste management, while ARTI Energy specializes on char production and briquetting of char dust. The list contains stakeholders involved individual and organizations already active in the charcoal or char-briquette sector or enterprises in the waste management business, as these were assumed to have the highest potential to become entrepreneurs producing char. Based on this initial list of stakeholders the method of chain referral sampling technique was used (snowball sampling), where the researcher interviewed the subjects and asked them to help identify people with a similar trait of interest. All identified stakeholders were categorized into clusters based on their main type of economic activity.

2.2.2. *Assessing the stakeholders*

A Multi Criteria Decision Analysis (MCA) was conducted, using the additive model as the multi-attribute value function (Eisenführ et al., 2010) to qualitatively assess the degree of suitability of the identified stakeholders to engage in a biowaste-to-char-dust business. In collaboration with experts of BORDA TZ and ARTI Energy, a list of objectives (or criteria) were developed that should be fulfilled by stakeholders to qualify as suitable entrepreneurs. Some of the objectives partitioned into sub-objectives as shown in Table 1. To generate the list of objectives, the procedure followed the approach suggested by Bond et al. (2008), where experts were first asked to list what they would consider the most important objectives. Then, in a second step they were confronted with a list previously brainstormed and elaborated by the authors and the deviations and overlaps were discussed to achieve consensus. The objectives were then assigned weights using the Swing and the Reverse Swing methods (Lienert et al., 2011). Table 1 shows the objectives ranked in descending order based on the elicited weights.

Table 1: Objectives, sub-objectives and weights considered in the MCDA

Objectives	Sub-objectives	Weights
High level of commitment	Self-involvement in char-dust production Willing to run a charcoal business Willing to receive training in carbonization	0.303
High level of technical expertise	Experience managing waste Knowledge on carbonization technology Experience running machinery	0.242
High accessibility to required infrastructure	Ownership of transport equipment Ownership of carbonization technology Investment capacity	0.212
High accessibility to dried biowaste	Amounts managed Existence of producers nearby	0.121
High accessibility to required space	-	0.076
High leadership experience	Experience leading groups Experience leading a business	0.045

All materials used in the interviews were available in English and Swahili. The interviewees were first given a brief introduction about carbonization and the related aspects regarding technology such as reactor construction, operational aspects, output products and potential revenues. Different existing carbonization technologies, as shown in Emrich (1985), were presented. Two assumptions were explained to the interviewees: 1) carbonization kilns can be operated in a cheap way; and 2) a main customer for the produced char-dust is ensured, which could safeguard the financial viability. Several questions were then asked in a structured and guided interview format to assess how the interviewed individual/organization meets the objectives and sub-objectives. Matching of objectives was scored using a scale of 0 (worst performance) to 5 (best performance). In the case of sub-objectives, these were assigned equal weights and scores were averaged. Overall performance score for each stakeholder were obtained by using a linear additive model, based on a weighted sum of the scores obtained for the objectives (Gregory et al., 2012). To estimate the final score per stakeholder cluster the final scores of each stakeholder in that cluster were averaged.

2.3. Assessment of enabling environment

The enabling environment is understood as the combination of six key determining elements that influence the production and consumption of char-briquettes (Figure 4). For this assessment, on one hand, a detailed review of local and legislative documents was conducted. On the other hand, the identified stakeholders were interviewed by means of a structure questionnaire.

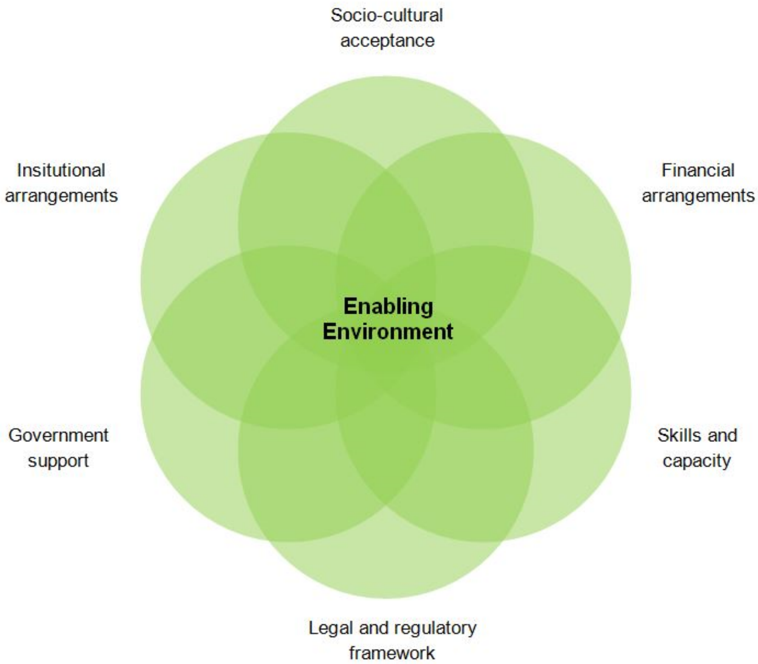

Figure 4: The six elements of the enabling environment (adapted from Lüthi et al., 2011)

3. RESULTS AND DISCUSSION

3.1. Technical results

As shown in Table 2, for both series and varying setup of experiments, results did not show significant variations in char yield. Compared to results published in Lohri et al., (2015a) char yields are lower (35.7% in Lohri et. al., 2015a). The lower char yields could be due to smaller particle size (4 cm × 20 cm) than of those used by Lohri et al. (2015a) (20 cm × 70 cm). Furthermore, in two of the experiments approximately 15-20% of the feedstock was not fully carbonized, and was not considered when calculating the mass yields. Also lower char yield could be attributed to a higher level of combustion inside the pipes, in other words an overly supply of oxygen which counteracts the pyrolysis process. Fixed carbon yields are between 15.4 and 16.6 with the exception of one experiment with a FC of 23.5%. These results compare well with results of 19% published in Lohri et al. (2015a).

Table 2: Summary of carbonization results

Exp. N	Duration (min)	Max. Temp. (°C)	Heating rate (°C/min)	Char yield (%)	FC yield (%)	HHV (MJ/kg)	ER
1.1	30	655	17.2	25.7%	15.53%	22.3	1.14
1.2	29	539	14.2	26.9%	23.47%	24.3	1.49
1.3	29	448	10.0	23.4%	15.59%	22.8	1.02
2.1	38	255	6.4	24.2%	15.36%	23.8	0.57
2.2	70	365	8.1	26.6%	16.58%	24.1	0.65

All chars produced, showed high heating values (HHV) (21.6 – 24.3 MJ/kg_{db}) similar to those of bituminous coal. When comparing the char with the original cardboard feedstock, the volatile solids (VS) content decreased from 79% in cardboard to 8.5 – 39% in the char, where lower values indicate a higher quality char. The fixed carbon (FC) increased considerably from 7.7% (cardboard) to values of 49 – 57% in the char (figure 5).

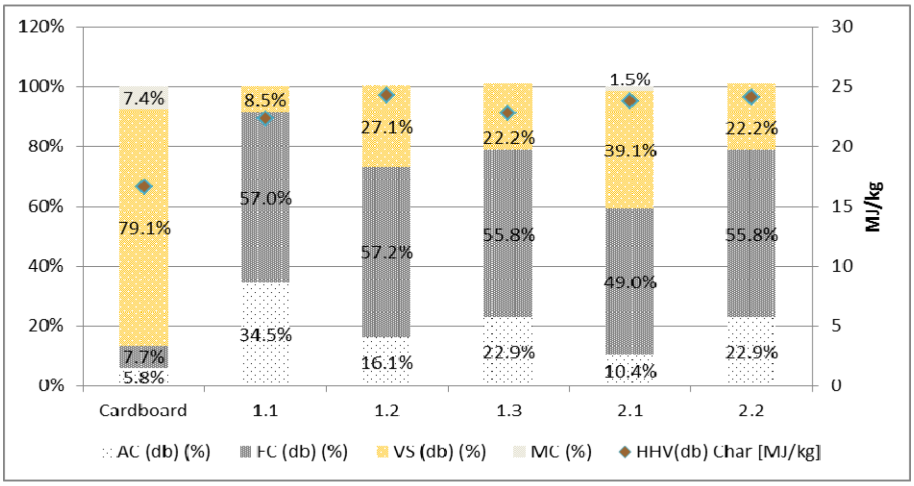

Figure 5: Proximate analysis and HHV of cardboard and obtained chars

As shown in Table 2, the second series of experiments with two barrels stacked above each other had longer processing durations (38-70 min), lower maximum temperatures, and lower heating rates. This results in an energy ratio significantly below 1 which indicates that more energy content of LPG was utilized to fuel the process compared to what energy content is gained by the char. The stacking of two barrels is the most likely cause for this, as the higher vertical stack increases the flow velocity of hot air by a chimney effect, thus removing the hot air from the system and diminishing the heating rate for the lower drum and the pyrolysis process. For the experiments with one barrel however, all results show energy ratios above 1 (Figure 6). In the best case (experiment 1.2), 0.67 MJ of LPG were needed to generate 1 MJ of char.

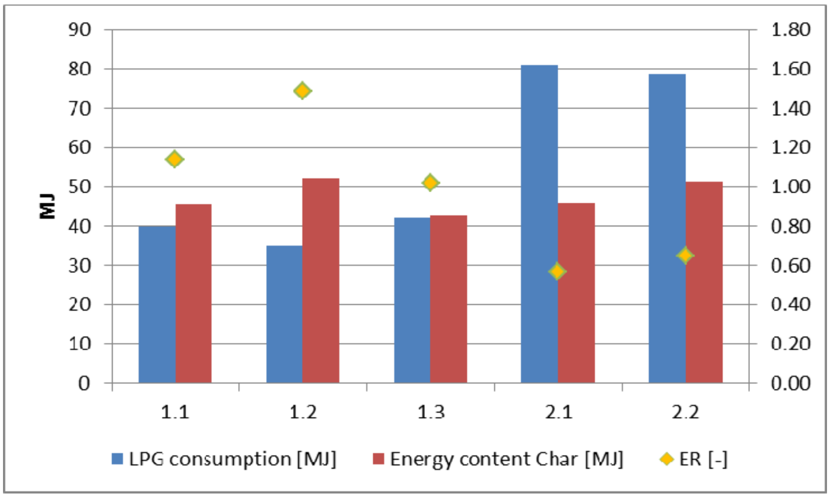

Figure 6: Energy consumed and generated with the respective energy ratio per experiment

3.2. Stakeholder analysis and assessment

A total of 62 local stakeholders were identified and interviewed. These are stakeholders involved in solid waste management sector either as waste generators (small companies, market, food processing industries), waste collectors (formal enterprises and informal enterprises, waste pickers), formal and informal recycling enterprises. In addition three different levels of authorities were also included; one leader of each municipality (Ilala, Kinondoni and Temeke), ward- and sub-ward leaders from each municipality. With regard to enterprises involved in the charcoal business, several companies of different sizes were included. Finally, several NGOs involved in different activities related to waste or forest management were also included in the assessment. All these stakeholders were categorized into 7 clusters: 4 clusters relate to stakeholders linked to SWM activities, 2 clusters relate to stakeholders linked to char practices and the last cluster to NGOs. Table 3 provides an overview of the stakeholder clusters, the estimated amount of stakeholders in each cluster, and the number of stakeholders interviewed.

Table 3: Overview of stakeholder cluster, cluster size and number of interviews held in each cluster

Stakeholder Cluster			Estimated N°	Interviewed
Solid waste sector	**Generators**	Small companies	$> 10^6$	4
		Markets	50-100	3
		Industry	25-50[1]	4
	Collectors	Environmental Groups, CBO's and waste collectors	200-250	18
		Junkshops	unknown[2]	4
	Recycler	Recyclers	unknown[2]	3
	Institutions	Municipalities	3	3
		Wards	90[3]	5
		Sub-Wards	423	5
Char sector	**Charcoal Business**		92,000[4]	3
	Briquetting Business		10-20	4
	NGO's and NPO's		200	6

[1]Out of 200-250 registered industries in DSM, 25-30 are food processing industries and thus generated biowaste (Tanza YP, undated)
[2]Impossible to estimate as a big number works on informal basis
[3]Breeze, 2012
[4]Estimates for Tanzania. Around 10% of these are officially employed for charcoal production (World Bank, 2009)

Table 4 shows the average scores as calculated for each stakeholder cluster for each objective, as well as the final average score for each cluster. The final score for each cluster was used to rank the list in descending order.

Table 4: Averaged weighted sum of scores per stakeholder cluster. Higher scores are highlighted with a darker background color.

		Objectives						Final score per cluster	SD[1] within cluster
		Commitment	Technical expertise	Infrastructure	Dried biowaste	Space	Leadership		
	Weights	*0.303*	*0.242*	*0.212*	*0.121*	*0.076*	*0.045*		
Stakeholder types	**Briquette business**	4.4	4.8	3.9	3.3	0.0	4.8	**3.9**	**0.6**
	Waste collectors	4.4	3.7	2.8	4.8	3.1	4.5	**3.8**	**0.7**
	Industry	2.1	3.6	4.4	4.3	4.5	5.0	**3.5**	**0.6**
	Municipalities	3.0	4.0	2.7	5.0	0.0	5.0	**3.3**	**0.7**
	Junkshop	3.8	2.3	1.5	5.0	2.0	2.9	**2.9**	**0.6**
	Recyclers	3.1	3.7	1.7	2.3	2.3	4.0	**2.8**	**1.0**
	Markets	2.9	2.3	1.7	5.0	1.0	5.0	**2.7**	**0.4**
	NGO	2.9	3.0	2.4	2.5	0.0	5.0	**2.6**	**0.6**
	Wards	3.9	1.1	1.1	4.6	1.2	5.0	**2.6**	**0.2**
	Small companies	3.3	1.5	1.6	2.3	2.8	4.6	**2.4**	**0.2**
	Charcoal business	3.6	0.6	1.4	3.0	0.0	4.2	**2.1**	**0.5**
	Sub ward	3.1	0.5	0.8	2.6	0.0	5.0	**1.8**	**0.4**
	Averaged	*3.4*	*2.6*	*2.2*	*3.7*	*1.4*	*4.6*		

[1]*Standard Deviation among stakeholders within one cluster*

The two stakeholder clusters that scored highest are the current char-briquette producers and the waste collectors, whereas the sub-wards and current charcoal business scored lowest (Table 4).

The briquetting businesses scored very high for all objectives except for space, for which they scored the lowest value (0.0). They already know the sector and therefore have the highest score for technical expertise (4.8) and also scored high in the objective of having the required infrastructure (3.9). They are one of the most motivated stakeholder clusters (4.4).
The waste collectors also scored high for almost all objectives. They have good access to dried biwoaste (4.8) and also show interest and commitment towards carbonization of such waste (4.4). They have better access to space (3.1) but less access to the required infrastructure (2.8).

The sub-wards are the stakeholders that scored worst. They show a high score on leadership capacity (5), probably due to the fact that these elected sub-ward members, are inherently skilled in motivating and leading groups of people given their function. In spite of this high level of leadership capacity, the satisfactory scores with regard to commitment (3.1) and a moderate score on accessibility to dried biowaste (2.6), they scored very low in all remaining objectives. The charcoal businesses resulted with slightly higher scores.

Interestingly, "*high leadership experience*" is the objective where most stakeholder clusters scored very high (avg. 4.6). This was however the least weighted objective, and thus did not contribute much to increase the final scores. Furthermore, most stakeholders also obtained satisfactory scores for the objectives "*high accessibility to dried biowaste*" (avg. 3.7) and "*high level of commitment*" (avg. 3.4). On the other hand, "*accessibility to sufficient space*" to keep dry the biowaste as well as to carry out a smoke generating activity seemed to be the biggest bottleneck for most stakeholders (avg. 1.4). Considering the high urban density of Dar es Salaam this seems to be a generally valid constraint. Furthermore, the interviews with the stakeholders revealed that the financial prospect is most motivating for most stakeholders, more than the environment and the social status (Zermin, 2015).

Standard deviations shown in the last column of Table 4 display the inner variability of the final weighted score within each group. The cluster "recyclers" shows the biggest inner variability, where the weighted scores ranged from 2.2 to 4.2. Within the best scoring clusters, the weighted scores also ranged between 2.9 – 4.6 and 2.6 – 4.8 for the briquette business and the waste collectors respectively. This indicates that although these groups could share similar characteristics, often the individual component is determinant when assessing the suitability of stakeholders.

4. ENABLING ENVIRONMENT

The assessment of the six elements defining the enabling environment revealed some major constraints as well as some opportunities. Mwampamba et al., 2013 has already reported that despite the advantages of char-briquettes, which include price, burning time, environmental sustainability, consistent quality and the potential for product standardization, the customer interest and uptake to use this as a substitute for wood-based charcoal remains limited. Increasing tendency to use charcoal instead of alternative cooking fuels such as kerosene, LPG, ethanol-based fuels or electricity, is driven by a perception that charcoal is stably available and is perceived to have low price (Msuya et al., 2011, Akowuah et al., 2012; Lohri et al., 2016). The assessment of socio-cultural acceptance confirmed these findings and revealed that wood-based charcoal is a very strongly rooted commodity. Crucial aspects that determine the choice of the consumer are reliable availability, burning properties, emissions and smell (Zermin, 2015). While alternative fuels such as kerosene, LPG, ethanol-based fuels or electricity are in fact expensive for most households and public institutions (i.e. schools or hospitals) (Agbemabiese et al., 2012) or do not provide an acceptable charcoal substitute (Mwampamba et al., 2013) this is not valid for char-briquettes. Char-briquettes are often cheaper than charcoal and do not require big investments since the same cooking stoves could be used. Char-briquettes made from agricultural waste in DSM were sold for 600 TZS per kg in 2013, whereas wood-based charcoal was sold for 1400 TZS/bag (0.9 – 1.3 kg) and for 47,500 TZS/bag (80 – 120 kg) (Lohri et al., 2015b). Nevertheless, consumers still predominantly prefer the traditional wood-based charcoal. The price of briquettes therefore shows to be a less determinant factor than other aspects, such as burning properties. Due to higher ash content of some biowastes, the calorific value of char-briquettes is lower and combustion characteristics are slightly different compared to wood-based charcoal (Lohri et al., 2016). Table 5 provides an overview of the general differences between wood-based charcoal and char-briquettes.

Table 5: Differences between wood-based charcoal and charcoal briquettes (adapted from Lohri et al., 2016)

	Wood-based charcoal	Char-briquettes
Raw material	wood	Agricultural and specific urban biowaste, charcoal dust
Energy value	31 – 33 MJ/kg	22-29 MJ/kg
Ash content	< 5%	10 – 30 %
Ease of lighting	Easy to light	Harder to light (due to higher ash content)
Length of burn	Fast burning (high energy & low ash)	Slow burning (higher ash content)

The traditional charcoal sector economy provides income to several hundred thousand households in both urban and rural areas in Tanzania. Charcoal alone was estimated to contribute US$ 650 million annually to Tanzania's economy (US$ 350 million in DSM alone), which is not far from the US$ 700 million of foreign direct investment in the country in 2010, and it is more than 6 times larger than the combined value of coffee and tea production (World Bank, 2009). However, most charcoal is harvested without paying for the raw material (wood) or paying licenses. This is in contradiction with the current Forest Act (2002). Only one fifth of the charcoal consumed in the city a tax is levied. Of the charcoal transported into Dar es Salaam, 90% remains unreported in official records, and most of it is imported into the city at night (Norconsult, 2002). Such actions also violate the current Forest Act (2002) and cause loses up to 38 million shillings per day (almost 16,000 USD) to the national and regional government (Malimbwi and Zahabu, 2008). The small fraction of taxes collected enter into the general national or municipal budget and are not used for investments in improved technologies and long-term sustainable forest management. Thus the price of charcoal does not reflect its real cost. It is thus essential to improve the regulatory and fiscal framework of the sector, else the market price of char-briquettes or even that of legal and sustainably produced charcoal will always be undercut by unregulated and unsustainable products (World Bank, 2009).

As for skills and capacity of those involved in charcoal and char-briquette production, there are several factors that hinder a shift towards innovation. Over 40% of charcoal producers have no formal education (Malimbwi and Zahabu, 2008). The vast majority are farmers who are engaged in charcoal production as an alternative income-generation activity in addition to agriculture and who produce charcoal from trees felled during land clearing (Lohri et al., 2015b). New entrepreneurship in carbonization is furthermore discouraged since businesses would need to get an official permit or license from the National Environmental Management Council. Finally, the existing briquetting initiatives are yet uncoordinated and isolated, which makes difficult to estimate the total volume production (Lohri et al., 2015b).

As for institutional arrangements and government support, responsibilities in the charcoal sector are shared by four ministries. These include the Division of Environment (DoE) within the Vice President's Office (VPO), the Ministry of Energy and Minerals (MEM), the Ministry of Natural Resources and Tourism (MNRT), and the Prime Minister's Office-Regional Administration and Local Government (PMO-RALG). In the value chain of charcoal production, which involves wood extraction up to energy consumption, the responsibilities are fragmented in multiple ministries. This hinders a quick and transparent flow of information. With recent legal changes, PMO-RALG, through its regional and district offices, together with village governments increasingly play a central role in forestry policy and practice. The next step of charcoal transportation and trade is in the responsibility of the Forestry and Beekeeping Division (FBD) of the MNRT, while MEM becomes involved as the primary policy lead on energy use. The Division of Environment (DoE) has authority to oversee and coordinate the aforementioned line ministries to ensure protection of the environment, including requirements for environmental impact assessments. This complicated division of tasks contributes to the aforementioned lack of fiscal empowerment, which hinders the possibilities of more sustainable practices or the marketability of new products, such as char-briquettes.

Over the years, each of these ministries has issued a range of legal and policy documents that have either direct or indirect impacts upon the charcoal sector. However, there is no comprehensive policy, strategy, or legal framework in Tanzania addressing the charcoal sector, which is characterized by a lack of legal empowerment and a low capacity for policy implementation. In spite of the charcoal sector gradually increasing its presence in legislative documents (National Energy Policy, 2015; Environmental Management Act, 2004; Forest Act, 2002), a very slow change in consumption and production patterns is observed. Some of these policies (i.e. National Energy Policy, 2015) encourage fuel switching which are unrealistic given the huge investments entailed and fail to recognize the reality of future consumption trends as well as the significant potential of biomass energy. In response to the energy crisis, however, Tanzania has been re-evaluating their energy policies to develop a new biomass energy strategy (BEST, 2014). This document represents a cornerstone as it is the first action plan, elaborated at the request of the Ministry of Energy and Minerals (MEM), which explicitly regulates biomass-to-energy activities. The strategy is meant to (i) ensure a sustainable supply of biomass energy, (ii) increase efficient and effective use of biomass energy and (iii) promote access to appropriate, alternative sources of energy. This action plan could foster the production and consumption of char-briquettes if more realistic, pragmatic and biomass-oriented energy policies are implemented.

Three main opportunities were identified for fostering char-briquette production and consumption. Firstly, acknowledging that 80% to 90% of urban households depend on unsustainable sources of charcoal for cooking (Mwampamba et al., 2013), implies that there is a potentially large and growing demand for conventional charcoal which will ultimately result in an increase in price. It is then when briquettes could tap into the market due to their similarity to charcoal, also in terms of infrastructure required for its use (cooking stoves), and thus have a competitive advantage to other cooking fuels (i.e. LPG; kerosene, etc.). Secondly, the growing environmental consciousness among consumers, together with sustainability issues being factored into their decision making, could result in an increase of the demand of cleaner fuels in the next years. Thirdly, the need to provide a management and treatment solution to an increasing amount of organic waste generated in DSM. Assuming that 30% of the approximately 2’500 tons of biowaste generated every day consist of suitable biomass for carbonization, and assuming a char yield of 25%$_{db}$, would result in a potential production of around 190 tons of char-dust per day. This would represent approximately 14% of the daily charcoal consumption. Including this sustainable fuel into the energy supply of DSM would not only increase the alternatives to charcoal but it would also contribute to improve the city’s current inefficient solid waste management.

5. CONCLUSIONS

All resulting chars produced by the newly designed and constructed reactor showed satisfactory high heating values (21.6 – 24.3 MJ/kg$_{db}$) although smaller char yields than those observed with the first experimental set up were observed. Experiments carried out with one barrel had favorable energy ratios ranging 1.02 – 1.49. However, the highest ER obtained in the trials with both barrels was not above 0.65. Further adaptations of the kiln are now underway, for instance to improve the combustion efficiency of the furnace, better control of the secondary air supply, reducing the heat losses and increasing the retention time of the air draft within the system.

The stakeholder analysis revealed that existing char-briquette producers and waste collectors are the most promising stakeholder clusters to become char-dust producers of biowaste. Both know the sector well and have some technical expertise, the required infrastructure and access to biowaste. On the other hand, the sub-wards and current charcoal producers scored low, due to their low technical expertise, lack of accessibility to infrastructure and lack of accessibility to space. Most stakeholders scored high for the objective “high leadership experience” and satisfactorily for “high accessibility of biowaste” and “high level of commitment”. On the other hand, accessibility to space to keep dry the biowaste as well as to carry out a smoke generating activity seemed to be the biggest bottleneck for most stakeholders, most likely due to the high urban density of Dar es Salaam. For all stakeholders, money is the main driver when it comes to starting a business on char-dust production from biowaste. As long as there is business potential in the sector, people will take it up, unless prohibiting initial investments are required.

The assessment of the enabling environment identified five core issues that hinder the development of a char-briquette market: (i) solid preference towards charcoal on behalf of consumers, (ii) lack of fiscal empowerment in the charcoal sector, (iii) lack of legal empowerment, (iv) low capacity for policy implementation and enforcement and (v) fragmentation of institutional responsibilities. Furthermore, customers show little flexibility when it comes to switching from charcoal to char-briquettes. The specific qualities of charcoal are preferred over those of char-briquettes, even if char-briquettes are sold at a lower price. However, char-briquettes consumption might experience an increase due to (i) the escalating demand for charcoal, which will ultimately impact on charcoal price, encouraging a product shift, (ii) a growing environmental awareness among the customers and (iii) the need to find solutions to a waste stream which shows promising characteristics as feedstock for char-dust production.

AKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the Swiss Agency for Development and Cooperation (SDC).

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