Original Article

WM&R

Waste Management & Research
2015, Vol. 33(2) 175–182

DOI: 10.1177/0734242X14564644
wmr.sagepub.com
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Urban biowaste for solid fuel production: Waste suitability assessment and experimental carbonization in Dar es Salaam, Tanzania

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Abstract

The poor state of solid waste management in Dar es Salaam (DSM), Tanzania, the large fraction of organic waste generated and a high charcoal consumption by city residents has triggered this research on carbonization of municipal biowaste. Char produced by the thermochemical conversion method of slow pyrolysis can be briquetted and used as cooking fuel alternative to wood-based charcoal. To explore the potential of biowaste carbonization in DSM, the most suitable organic wastes were selected and pyrolyzed in a simple, externally heated carbonization system developed as part of this study. A Multi-Criteria Analysis framework allowed to assess prevailing biowaste types regarding availability and accessibility, and respective suitability in terms of physical–chemical properties. The assessment, using data from a survey and lab analysis, revealed the following biowaste types with highest overall potential for char production in DSM: packaging grass/leaves (PG) used for transportation of fruit and vegetables to the markets, wood waste (WW) from wood workshops, and cardboard (CB) waste. Best practice carbonization of these biowastes in the pyrolyzer showed satisfactory char yields (PG: 38.7%; WW: 36.2%; CB: 35.7% on dry basis). Proximate composition (including volatile, fixed carbon and ash content) and heating value (PG: 20.1 MJ kg^{-1}; WW: 29.4 MJ kg^{-1}; CB: 26.7 MJ kg^{-1}) of the produced char also compare well with literature data. The energy and emission-related aspects of the system still require further research and optimizations to allow financially viable and safe operation.

Keywords

Biochar, carbonization, energy recovery, multi-criteria analysis, organic solid waste, slow pyrolysis

Introduction

As in many cities of low- and middle-income countries, the solid waste management system of Dar es Salaam (DSM) in Tanzania is characterized by a high fraction of organic matter (~60%), waste collection rates below 40% and inappropriate disposal methods such as burning, burying and dumping (Breeze, 2012). Besides the waste issues, the provision of affordable, reliable and sustainable cooking fuel for urban residents is still a major challenge, similar to other cities in developing countries (Maes and Verbist, 2012). Despite efforts in the past decade, wood-based charcoal remains the primary source of cooking energy in DSM. The proportion of households using charcoal rose from 47% in 2001 to 71% in 2007 and has reached 94% in 2011, causing severe pressure on forests and woodlands (World Bank, 2009; Felix and Gheewala, 2011; Msuya et al., 2011). This has triggered interest in developing technologies to transform urban organic waste to solid fuel, as it may provide a solution to both solid waste management as well as the escalating cooking energy costs.

Producing char, also referred to as carbonization, by slow pyrolysis is a process characterized by slow heating rate, long solid and gas residence times, and relatively low temperature in a largely inert environment (Basu, 2010). The thermochemical process for converting biomass in absence of oxygen into primarily char, secondarily gaseous and liquid products, has for centuries been known and applied for charcoal production from wood (Antal and Grønli, 2003). The carbonization process, which releases a distinctively pungent smell, does not require highly complex engineered systems, and its application is not limited to wood. Organic solid wastes generated in agriculture and urban

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Table 1. Assessment categories and sub-criteria.

A. Availability and accessibility aspects	B. Physical–chemical properties
1. Total quantity generated	1. Dry bulk density
2. Seasonal variation in supply	2. Particle size uniformity
3. Competing use	3. Moisture content
4. Cost of biowaste	4. Fixed carbon content
5. Degree of centralization	5. Ash content

environments can also be used as input material (Duku et al., 2012; Shuma, 2012). Waste-derived char can be further processed into charcoal-briquettes and used for household cooking as alternative to wood-based charcoal (Vest, 2003; Mwampamba et al., 2012).

While scientific literature about slow pyrolysis of municipal solid waste covers lab-scale experiments (e.g. Ryu et al., 2007; Phan et al., 2008; Velghe et al., 2011; Mitchell et al., 2013) and discusses relatively complex systems for mixed waste in industrialized countries (Chen et al., 2014) or low-cost retorts for wood-charring (Adam, 2009), limited research is available on decentralized carbonization of different types of municipal organic solid waste applied in developing countries. This paper presents research on the potential of urban biowaste for char production in DSM. It provides an assessment framework for selection of the most suitable waste for char production. The three most promising biowaste types were carbonized in a simple, small-scale experimental pyrolysis unit, which was critically evaluated in terms of its technical functionality, financial viability and dissemination potential.

Materials and methods

Biowaste assessment

Based on literature review and semi-structured interviews with stakeholders in the academic, public and private waste sector, streams of biowaste generated in the city were pre-selected for further assessment. These include:

- bagasse (residue after sugarcane juice extraction);
- potato peelings;
- coconut shells/husks;
- packaging grass/leaves (used for transportation of fruit/vegetables to markets);
- trimmings/pruning;
- cardboard;
- wood waste (from carpentries and saw mills);
- seaweed.

The two main categories and respective sub-criteria used to characterize the waste types are shown in Table 1.

Criteria in category A (methodology adapted from Chardust and Spectrum Technical Services, 2004) help to determine whether the wastes are available, preferably at no cost, throughout the year to allow continuous production of char. Data were obtained through semi-structured interviews with city municipal officers, waste producers, market administrators and stakeholders in different institutions, waste collectors, recyclers, and customers of waste-derived products. Observations, estimations, and measurements of volume and weight of waste were conducted. Waste samples were preserved in air-tight sealing bags for laboratory tests. Criteria in category B inform about whether the waste is suitable for carbonization with a minimum of pre-treatment and if the properties are suitable to produce a high-quality char fuel. Moisture content was determined by measuring the weight loss after the fresh samples were dried at 105°C according to ASTM E1756-08 standard test method for total solids in biomass. The volatile matter content was obtained by determining the weight loss after heating the dried samples for 7 min at 950°C according to ASTM E872-82 standard test method. The ash content was measured by the weight loss after burning the dried samples in a muffle furnace at 575°C according to ASTM E1755-01. Fixed carbon was calculated by summing the percentage of ash and volatile matter and subtracting it from 100%. For determining the bulk density, a sample was being filled according to EN 15103 into a cylindrical container of 50 L volume. The filled container was then exposed to controlled shock by dropping it three times from 150 mm height onto a wooden floor, after which the filling volume created by the shock operation was refilled and levelled to the rim of the container. The net weight was determined and related to the container volume.

Biowaste suitability for char production in the city was conducted using a Multi-Criteria Analysis (MCA) procedure for both category A and category B. The data obtained from survey and interviews were converted by the authors into scores ranging from 1 to 5 (1: low suitability; 5: high suitability) with a clearly defined attribute-to-score key as shown in Table 2. The scores were then presented to experts for re-evaluation and confirmation. Attribution of scores depends on the scale of char production and relative costs involved. In this study, a pyrolysis system capable of carbonizing 1 tonne of biowaste per day was used for the calculation and scoring. The system is thus characterized by:

- one batch (200 L volume) contains a maximum of 50 kg of waste;
- maximum of 8 batches per day can be processed, i.e. 400 kg waste can therefore be pyrolyzed in one reactor unit per day.

A pyrolysis system with two 200 L drum reactors can thus pyrolyze 800 kg of waste per day when operating in a semi-batch mode. To allow flexibility in case of irregular and impure waste supply, another 25% was added to obtain the minimum required biowaste supply per day of 1 tonne.

Part A of Table 2 presents the attribution of scores regarding availability and accessibility. To guarantee continuous operation highest score was ascribed if the total amount generated exceeded the double of the required amount of 1 tonne day^{-1}, lower scores were ascribed for reduced quantities in steps of 25% less the

Table 2. Attribute-to-score keys for assessment of A. availability and accessibility aspects (adapted from Rweyemamu, 2014) and B. physical-chemical properties of biowaste in DSM.

A. AVAILABILITY and ACCESSIBILITY CRITERIA		Score 1	Score 2	Score 3	Score 4	Score 5
Total amount generated	*(tonnes day^{-1})*	<0.25	0.25–0.5	0.5–0.75	0.75–1.0	>1.0
Seasonal variation	*(tonnes day^{-1} available)*	<1	–	1–2	–	>2
Competing use	*(tonnes day^{-1} available)*	<1	–	1–2	–	>2
Cost of waste	*(USD tonne^{-1})*	>47	31–47	16–31	<16	0
Degree of centralization	*(tonnes day^{-1} location^{-1})*	<1	–	1–2	–	>2
B. PHYSICAL–CHEMICAL PROPERTY CRITERIA		**Score 1**	**Score 2**	**Score 3**	**Score 4**	**Score 5**
Dry bulk density	*(kg dry matter m^{-3})*	1-50	50–100	100–150	150–200	>200
Particle size uniformity	*(qualitative)*	Not uniform		Semi-uniform		Uniform
Moisture content	*(%)*	80-100	60–79	40–59	20–39	0–19
Fixed carbon content	*(%)*	0-3.9	4–7.9	8–11.9	12–15.9	>16
Ash content	*(%)*	>10	7–9.9	4–6.9	1–3.9	<1

1 USD = 1600 TZS (as of March 2014).

required minimum amount. Lowest score was given if the supply is below the minimum required. For the criteria of seasonal variation, lowest score was accredited if the supply falls below the required minimum daily feeding load of 1 tonne, whereas highest score means that at least more than double of the required amount is available at all times during the season. Existing uses of waste affects the criteria of 'competition for the supply'. A negative consequence results only if the remaining waste amount (to be used for carbonization) is less than the required daily minimum amount of 1 tonne. Waste generators who charge for their waste leads to reduced profitability. Thus, it is most beneficial to find wastes which are free of cost. Ideally, waste should also be available in bulk at one location as widely dispersed wastes in small quantities will result in high transportation costs and collection time. This is described by the criteria 'centralization' where highest score is attributed if the waste generation at one location exceeds double the required daily amount, while lower scores were assigned if it requires more than one location to collect the minimum amount.

Part B of Table 2 presents the attribute-to-score key for the physical–chemical properties. High bulk density (on dry matter basis) is preferred and received highest score as it reduces transportation cost and allows more dry substrate to be pyrolyzed per batch. Uniformity of particle size is beneficial to avoid pre-treatment before carbonization, predictability of pyrolysis process and uniformity in charring. High moisture content (as collected) increases transportation cost and substantially reduces its suitability as drying is a highly energy-intense process with adverse effects on the energy balance of the pyrolyzer. High fixed carbon reflects high potential for high char yield, while high ash content (inert inorganics) reduces the quality of the fuel (heating value of the char product) and increase abrasion and equipment wear during briquetting.

Weights for each sub-criterion to indicate their relative relevance for fulfilling the objective of cost-effective carbonization (1: low importance; 5: high importance) were discussed in focus group discussions by solid waste and bioenergy experts. The consensual weights were multiplied by the assigned scores. The calculated sum of weighed scores for each biowaste allowed for a comparison and ranking of the assessed waste types. To avoid losing crucial information in the MCA process, waste types that received lowest score of 1 in any of the sub-criteria are written in bold, implying this aspect needs careful examination to ensure that successful long-term operation of the pyrolysis system is not threatened.

Slow pyrolysis system

The development of an experimental pyrolysis unit was guided by the criteria low production costs, local availability of materials, ease of construction and operation, simple maintenance and repairing, easy control of carbonization process, recycling of pyrolysis gases to reduce emission and for energy recovery, simple measurement of supplied energy, ergonomics for one operator and safety.

Construction of an experimental unit placed at the university campus was initiated after studying different approaches based on literature and reports.

Analysis of pyrolysis. Three waste types which rank highest in the assessment were used for pyrolysis experiments. Initial weight of the substrate was measured using a digital hanging scale. Temperature inside the reactor, in the brick kiln housing, and flue gases in the chimney were continuously recorded. Energy consumption was measured by weighing the LPG cylinder before and after each batch and calorific value was calculated using a conversion factor of 46 MJ kg^{-1} (lower heating value of LPG). Composition of feed material and char formed were determined using proximate analysis methods as described above. Char yield was calculated on wet basis and dry basis:

$$y_{char} = \frac{m_{char}}{m_{waste}} \quad (1)$$

Carbonization efficiency was calculated by the fixed-carbon yield (y_{fc}), according to

$$y_{FC} = y_{char} * \frac{\%\,FC}{(100 - \%\,feed\ ash)} \quad (2)$$

where FC is the fixed carbon content of char and % feed ash is the percentage ash content in the raw waste (Antal et al., 2000).

In addition, the higher heating value (HHV) of a char sample of each waste type was determined using a correlation formula based on proximate analysis (Parikh et al., 2005) and cross-checked by bomb calorimetry test:

$$HHV = 0.3536\,FC + 0.1559\,VM - 0.0078\,ASH \qquad (3)$$

where FC is the percentage of fixed carbon content, VM the percentage of volatile matter content and ASH the percentage of ash content in the char

Overall evaluation. The experimental pyrolysis system was critically evaluated in terms of functionality, safety and financial viability when operated with three types of biowastes. The measurement of LPG used as external heat served as a basis for calculation of potential alternative heat sources and respective quantities (e.g. wood, charcoal, char-briquettes, biogas). This in turn allowed examination of operational cost and benefits when operating such a facility in DSM with alternative fuels.

Results and discussion

Biowaste assessment for char production

The criteria on 'total amount of waste generated', 'competing use' and 'price of waste' were considered most relevant factors influencing overall availability and accessibility, and thus received the highest weights. 'Degree of centralization' was considered slightly less relevant, followed by 'seasonal variation'. Half of the assessed biowaste received the lowest score in terms of centralization, which means their availability at one location is not sufficient but requires collection from two or more locations to meet the daily required amount (1 tonne). This implies higher transportation cost.

Part B of Table 3 presents the score of pre-selected waste based on their physical–chemical properties suitability for char production. Potato peelings, coconut shells/husks, packaging grass/leaves, and wood waste are the waste types which did not receive the lowest score in any of the sub-criteria in this category (B). Seaweed revealed very low fixed carbon, high moisture and ash contents which substantially reduces its suitability for char production.

Figure 1 presents the overall results on availability and accessibility, and physical–chemical properties of the selected biowaste for char production in DSM. The biowastes with highest overall suitability are packaging grass/leaves, followed by wood waste and cardboard. Of the three, cardboard received the lowest score in the particle size uniformity criterion. However, this aspect is considered of low relevance. Seaweed has highest scores in terms of its availability and accessibility but shows lowest scores in physical–chemical properties, thus greatly reducing its overall suitability. Coconut shells/husks have good physical–chemical properties but its availability is considerably reduced by high competing uses, seasonal variation, and their highly dispersed waste-generation sources.

Table 3. Scores and weights attributed to availability and accessibility criteria (A) and physical-chemical properties (B) of biowastes in DSM.

	A. AVAILABILITY & ACCESSIBILITY ASPECTS										B. PHYSICAL-CHEMICAL PROPERTIES									
	Amount Generated		Seasonal variation		Competing use		Price of waste		Centralization		Dry bulk density		Particle size uniformity		Moisture		Fixed Carbon		Ash	
	tonnes day^{-1}	SC	tonnes d^{-1} avail.	SC	tonnes d^{-1} avail.	SC	USD t^{-1}	SC	tonnes d^{-1} and location	SC	kg (db) m^{-3}	SC	qualitative	SC	%	SC	%	SC	%	SC
Bagasse	1.5	5	1.2	3	1.4	3	0	5	0.14	1	48	1	Semi-u.	3	61.7	2	16.3	5	0.8	5
Potato peelings	9.0	4	8.1	5	6.3	5	31–38	2	0.63	1	108	3	Semi-u.	3	77.2	2	9.1	3	6.1	3
Coconut shells/husks	1.0	5	0.7	1	0.6	1	13–25	3	0.06	1	257	5	Semi-u.	3	11.8	5	18.8	5	1.2	4
Packaging grass/leaves	13.8	5	11.1	5	12.4	5	0	5	1.24	3	92	2	Semi-u.	3	11.2	5	17.4	5	7.7	2
Trimmings/pruning	1.0	5	0.6	1	0.7	1	31–47	2	0.07	1	55	2	Not u.	1	17.3	5	19.2	5	8.2	2
Cardboard	66.6	5	60.0	5	46.6	5	50–75	1	4.66	5	52	2	Not u.	1	7.8	5	12.3	4	7.0	3
Wood waste	72.3	5	65.1	5	14.5	5	19–31	3	1.45	3	143	3	Semi-u.	3	13.1	5	20.7	5	1.9	4
Seaweed	355.1	5	177.5	5	319.6	5	0	5	31.96	5	90	2	Uniform	5	80.9	1	0	1	39.1	1
Weight (1-5)	5		3		5		5		4		1		1		5		3		4	

SC: score; db: dry basis.

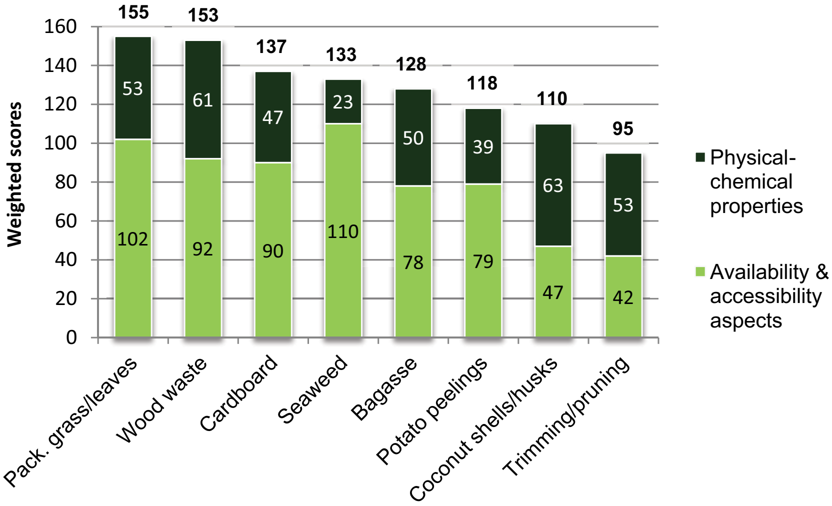

Figure 1. Overall results of biowaste assessment for char production in DSM.

Slow pyrolysis system

Design and construction. The designed carbonization unit consists of three main components (Figure 2):

I. pyrolysis reactor;
II. heating system;
III. heat-retaining brick kiln.

A metal barrel (200 L), which is widely available from road-side container vendors, was used as reactor. Inside the kiln, made of burnt clay bricks, the barrel is placed horizontally on guiding metal rails. The reactor was heated by two large burners (Figure 2). At the start, in the initial drying stages of pyrolysis, a 2 cm vent hole in the barrel is aligned to a temporary and removable chimney pipe to emit the gases out of the kiln. When the whitish coloured smoke (water vapour) changes its colour to yellow/brown (flammable gases such as CO, H_2, CH_4) the barrel was rotated by 180° so that the vent hole in the barrel is aligned to direct the flammable pyrolysis gases to the LPG burners. This reduces the requirement of fuel for external heating and eliminates CH_4 and CO pollution emissions from the pyrolysis reaction. When the pyrolysis gases exiting the vent hole extinguish this indicates the end of the pyrolysis process. The burners were switched off and the barrel removed from the kiln and left to cool outside the kiln. Another barrel was then loaded immediately to take advantage of the still hot kiln (semi-batch operation).

Pyrolysis experiments. Based on the biowaste assessment (see above), three substrates scoring highest (packaging grass/leaves, wood waste and cardboard) were experimentally charred in 10 trial run batches. Table 4 presents a summary of the batches done in best-practice-mode for each substrate and the waste type and process are as follows.

Packaging grass/leaves. The nature of packaging grass differs and depends on the location in the country where the fruits and vegetables originate. The packaging grass used was a mixture of rice straw (about 60%) and banana plant leaves. The 200 L drum could only be filled with 6 kg of sun-dried waste with a moisture content of 11% and pyrolysis was completed after 65 min, leaving behind 2.15 kg of char (4% moisture). Energy consumption rate per char produced was 45.14 MJ kg^{-1}, which is still substantially higher than the analysed energy content of the char (20.14 MJ kg^{-1}).

Wood waste. Wood shavings were obtained from wood workshops. A total of 13 kg (22% moisture) was loaded and pyrolyzed for 125 min, obtaining 3.9 kg char (6% moisture). Comparison of energy consumed (40.35 MJ kg^{-1} char produced) and energy contained in the char (29.44 MJ kg^{-1}) again showed an unfavourable balance.

Cardboard. Corrugated cardboard off-cuts with sizes between 20 cm × 70 cm and 4 cm × 20 cm were obtained at a nearby cardboard box factory. A total of 15 kg of unshredded cardboard (moisture 7%) was pyrolyzed for 130 min, reaching a peak temperature of 470°C. A total of 5.14 kg of char was formed with a moisture content of 3%. Energy consumed was 32.93 MJ kg^{-1} char produced and thus higher than energy contained in char generated (26.67 MJ kg^{-1}).

The average char yield from all 10 experimental batches was 31.3% on wet basis and 39.1% on dry basis, whereas average fixed carbon yield was 21.3%. The obtained results are comparable to data found in literature, where average char yield of different wood types are reported to be 30.5% (wet basis) and fixed carbon yield of 23.2% (Antal et al., 2000).

Figure 3 compares results derived from proximate analysis before and after carbonization. Ash fraction of charred packaging material is relatively high (31%), which can be attributed to contamination by sand and other foreign materials during collection from the field, handling and transportation.

Table 5 presents an overview of the results and compares them with data from literature. Overall the data obtained in the present study compare well with other studies. The measured HHVs of all chars are within the expected range. The empirical

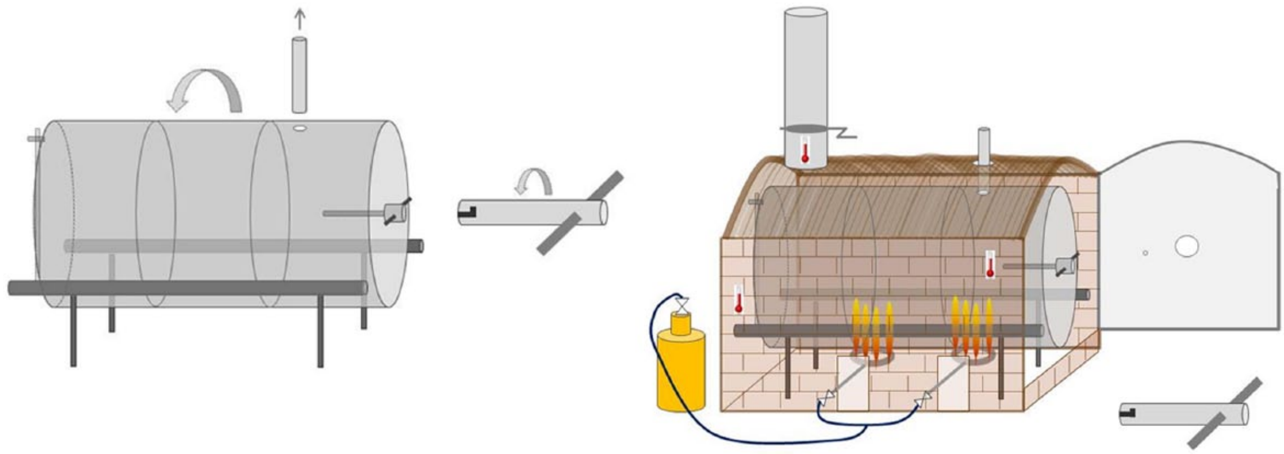

Figure 2. Scheme of experimental slow pyrolysis unit (left: pyrolysis drum, metal frame, rotating mechanism; right: complete pyrolysis system with heating system and heat retaining brick kiln).

Table 4. Summary of carbonization results (best-practice batches for each waste type).

	Loading rate (kg wet weight per batch)	Process time (min)	Peak temp. in reactor (°C)	Char yield (db)	Fixed carbon yield (%)	Energy consumption (MJ kg^{-1} char)
Packaging grass/leaves	6	65	402	38.7	20.3	45.14
Wood waste	13	125	415	36.2	23.3	40.35
Cardboard	15	130	470	35.7	19.8	32.93

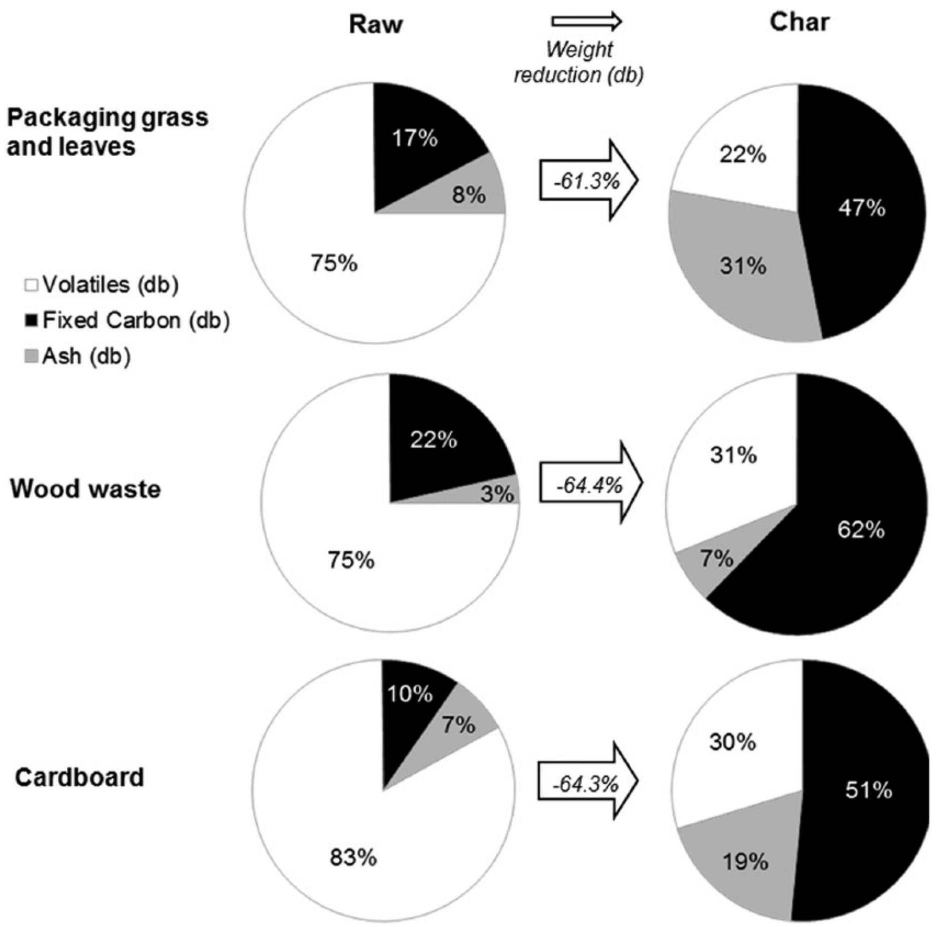

Figure 3. Proximate analysis composition of raw biowaste and charred product on dry basis (db).

Table 5. Comparison of results with literature data (p.s.: present study; lit.: literature, n/a: not available; HHV: higher heating value).

		Volatile matter (db; %)		Fixed carbon (db; %)		Ash (db; %)		HHV (db; MJ kg^{-1})	
		p.s.	lit.	p.s.	lit.	p.s.	lit.	p.s.	lit.
RAW	Pack. grass/leaves	76.8	68.3 [1a]	13.8	16.2 [1a]	9.3	15.5 [1a]	n/a	15.61 [1a]
	Wood waste	74.9	72.4 [1b]	21.6	25.0 [1b]	3.5	2.6 [1b]	n/a	20.93 [1b]
	Cardboard	82.9	82.1 [2,4] 84.7 [8]	9.8	6.0 [2,4] 6.9 [8]	7.3	6.8 [2,4] 8.4 [8]	n/a	14.48 [2,4]
CHAR	Pack. grass/leaves	22.3	23.0 [3]	46.8	43.0 [3]	30.9	25.3 [3]	20.14* 19.8**	18.59**[3]
	Wood waste	31.1	14.0 [5]	62.3	68.2 [5]	6.6	17.7 [5]	29.44* 26.82**	26.16**[5]
	Cardboard	29.7	10.6 [6] 22 [7]	51.5	78.8 [6] 48 [7]	18.8	10.7 [6] 20 [7]	26.67* 22.7**	29.43**[6] 20.25**[7]

[1]Grover et al. (2002) in Parikh et al. (2005): [1a] rice straw, [1b] saw dust
[2]Agarwal et al. (2014)
[3]Avenell et al. (1996): straw, lab-scale fixed-bed pyrolyzer
[4]Grammelis et al. (2009)
[5]Li et al. (1999): wood chips, externally heated lab-scale rotary kiln, 550°C
[6]Mitchell et al. (2013): corrugated cardboard, tube furnace, 480°C
[7]Phan et al. (2008): cardboard, lab-scale packed-bed pyrolyzer, 400°C
[8]Sørum et al. (2001)
[9]Yang et al. (2007)
*Analysed at CoET/UDSM (bomb calorimetry)
**Calculated (Parikh et al., 2005).

formula used for approximation of HHV using proximate analysis results (Parikh et al., 2005) showed acceptable correlation with analysis in a bomb calorimeter.

Cost analysis. Results from dried packaging grass/leaves were used to analyse the cost of running the unit in DSM. To pyrolyze 6 kg packaging grass/leaves, 2.11 kg of LPG were required. This could be substituted by 6.1 kg wood, 2.9 kg charcoal, 3.9 kg char-briquettes or 4.41 m^3 biogas (which would roughly require 44 kg of kitchen/market waste to be digested). The main assumption here is that the heat transfer efficiency with the alternative fuel is the same as when using LPG. With this assumption, the fuel operational costs could be reduced from 5.01 USD (LPG) to 2.29 USD (using char-briquettes). If revenues for sales of char remain identical (0.2 USD for the produced 2.15 kg char), the net loss could be reduced from 4.82 USD (LPG) to 2.10 USD (char-briquettes).

Impact of carbonizing biowaste in DSM

Daily generation of the prevailing biowaste types in DSM (bagasse, potato peeling, coconut shells/husks, packaging grass/leaves, trimmings/pruning, cardboard, wood waste, seaweed) amount to 520.3 tonnes, which correspond to 12% of the total municipal solid waste generated every day. If collected and carbonized with an efficiency of 30% this waste can be converted into 156.1 tonnes of char, which in turn could substitute roughly 10% of the daily consumed wood-based charcoal of 1600 tonnes (DSM Local News, 2010). When considering only the three most suitable biowaste types (packaging grass/leaves, wood waste and cardboard) only 153.7 tonnes of waste would be available per day (corresponds to 3.7% of total daily municipal solid waste generation), which could result in 46.1 tonnes of char (substituting 2.9% of total daily charcoal consumption). The impact on a city-wide scale is thus rather limited, but carbonization could nevertheless be an interesting valorization method for waste producers, collectors or service providers at material recovery facilities, who have continuous access to pure, dry and homogeneous biowaste.

Conclusion and recommendations

Using urban organic solid waste for char production was explored in DSM. Biowaste types were assessed and ranked regarding suitability for char production. A carbonization unit was designed and operated to study the quality of char formed, its energy requirements and to estimate the financial implications of operating such a system in DSM.

While the availability/accessibility assessment part requires good knowledge and a network of the city's waste sector to obtain the required information, rather basic equipment is needed (high-temperature muffle furnace, precision scale) for the physical–chemical suitability part of the assessment.

The assessment has to be adapted to the specific local circumstances and involve the main stakeholders as, e.g., the attribute-to-scoring key depends on the chosen pyrolysis technology, its scale and portability, and the attribution of weights to the sub-criteria is influenced by the exact project objectives.

The biowaste types selected proved to be suitable for carbonization. However, loading rate and pyrolysis time have consequences on the energy requirements, thus financial viability of the system, and need to be optimized.

The high char yields obtained from tests with various biowaste types demonstrated the technical functionality of the pyrolysis system. With adequate safety equipment (e.g. thermo-resistant gloves, dust mask for handling char powder), no substantial risk was observed during operation. Sufficient cooling phase (or use of water) after completion of pyrolysis and before opening of the barrel needs to be ensured to avoid complete char combustion when oxygen gets in contact with hot char. Assessments on the fate of heavy metals and products of incomplete combustion (PICs) such as polycyclic aromatic hydrocarbons (PAHs) in the char making and using processes are recommended to understand the health risks involved. An Environmental Impact Assessment could give further information on the broader consequences of this carbonization system. To increase the energy efficiency of the externally heated pyrolysis systems, improvement of heat supply and transfer rate is needed. Using hot exhaust gas from combustion to dry the biowaste of a next batch can also improve the fuel requirements.

A cost–revenue estimation revealed that financial viability of the experimental pyrolysis system is critical under the given circumstances. Operation costs can be reduced by changing fuel source and improvement of the heating system.

Acknowledgement

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

Declaration of Conflicting Interest

The authors declare that there is no conflict of interest.

Funding

This research was partially funded by the Swiss Agency for Development and Cooperation (SDC).

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