Sludge to Energy Enterprises in Kampala (SEEK) project

Co-pelletizing of faecal sludge with different biowastes for gasification

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January 2016

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Acknowledgements

This report was prepared as part of the SEEK (Sludge to Energy Enterprises in Kampala; www.sandec.ch/seek) project funded by the Symphasis Foundation and REPIC platform (Promotion of Renewable Energy and Energy Efficiency in Developing and Transition Countries). This study was also supported by the Swiss Development Corporation (SDC) and would not have been possible without contributions by Mohammed Babu (NWSC), Wim Getkate (CREEC), Andrew Kabuga (NWSC), Angelo Kwitonda (NWSC), James Maiteki (NWSC), Rita Nakazibwe (Makerere University), Martin Orwiny (NWSC), Smith Tukahirwa (CREEC), Paul Waiswa (NWSC) and other staff at the NWSC (National Water & Sewerage Corporation) Lubigi Wastewater and Faecal Sludge Treatment Plant for their support in this study.

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Introduction

Kampala, the capital of Uganda has a population of approximately 1.5 million people (Ugandan Bureau of Statistics, 2014). In Uganda, 94% of the population use onsite sanitation technologies such as pit latrines or septic tanks which are not connected to a sewer (Ugandan Ministy of Water and Environment, 2014). This results in the production of large amounts of faecal sludge (FS) (Strande, 2014). Currently, large amounts of FS are discharged untreated directly into the urban environment, jeopardizing public and environmental health. According to the Ugandan Ministry of Water and Environment, in Uganda, FS from 30% of latrines is discharged into the environment (Ugandan Ministy of Water and Environment, 2014). In Kampala, a treatment capacity of only 400 m^3 FS/day exist whereas > 600 m^3 FS/day are being collected (Orwiny, personal communication). Among others, one reason for inadequate FS management are insufficient financial capacities. Resource recovery from FS treatment endproducts such as use as soil conditioner, solid fuel or feedstock for biogas production can provide financial resources to offset FS management costs and work towards providing sustainable and safe sanitation (Diener et al., 2014). The SEEK (Sludge to Energy Enterprises in Kampala, www.sandec.ch/seek) project researches resource recovery from FS through FS pelletizing and gasification.

Gasification can use biomass such as wood chips, coffee husks, or rice husks to produce a gas which can be combusted for heat or electricity production. In contrast to large-scale gasifiers, small-scale gasifiers (e.g. the 10 kW Power Pallet from All Power Labs, Berkley, USA) have higher requirements in terms of fuel supply.

- Homogeneous fuel size.
- Low moisture content (< 12%, the lower the better).
- High calorific value (> 15 MJ/kg TS, the higher the better).
- Low ash content (< 30%, the lower the better). Only large-scale gasifiers can cope with higher ash contents (Centre for Research in Energy and Energy Conservation, personal communication).

Dewatered FS (e.g. from drying beds) has unsuitable fuel properties for gasification (Byrne et al., 2015; Gold et al., submitted-b). Pelletizing of FS can be used to produce a homogeneous fuel size. Various biomass pelletizers exist on the market. However, they commonly only operate with biomass with a moisture content of 10 to 15%. As FS commonly has a moisture content > 95% this means costly and space intensive drying is required before pelletizing and gasification (Dodane and Ronteltap, 2014; Gold et al., Submitted-a; Ståhl and Berghel, 2011). To recover energy from wet biomass, Bioburn AG (www.bioburn.ch) developed a pelletizer which is able to pelletize biomass at around 50% moisture content. This has the potential to reduce energy and costs required for drying. Preliminary research suggests that FS pellets can be dried more cost-effectively to a moisture content of 10% compared to drying beds.

FS also does not meet the requirements for ash content and calorific value (Byrne et al., 2015; Gold et al., submitted-b). Therefore, this study investigates whether urban biowastes can be co-pelletized with FS with the Bioburn pelletizer in order to produce a solid fuel with a homogenous fuels size, reduce the ash content and increase the calorific value for energy recovery through gasification. Further, the study investigated whether cheap commercial moisture meters can be used to monitor drying of the pellets to replace timely laboratory-based analysis.

Materials and Methods

This study was conducted at National Water and Sewerage Corporation (NWSC) Lubigi Wastewater and Faecal Sludge Treatment Plant (in the following referred to as NWSC Lubigi) in Kampala, Uganda. Laboratory analysis were conducted at the Public Health and Environmental Engineering Laboratory at the College of Engineering, Design, Art and Technology at Makerere University.

Experimental setup

In this study, FS was co-pelletized with biowastes with the Bioburn pelletizer (model BPM-X108). A drawing of the Bioburn pelletizer and the installed Bioburn pelletizer at NWSC Lubigi is included in Figure 1 and Figure 2.

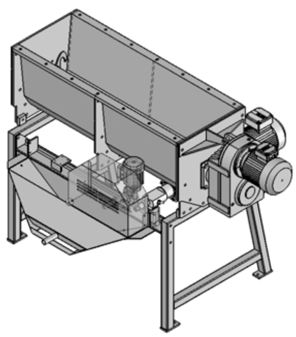

Figure 1: Drawing of the Bioburn pelletizer (Bioburn AG, 2015).

Figure 2: Bioburn pelletizer installed at NWSC Lubigi

To identify which FS and biowaste ratio produces optimal pellets, 10 kg FS was pelletized with variable quantities of four different biowastes and a binder. Preliminary experiments demonstrated that 100% FS with moisture content ranging from 30 – 60% produces good pellets with the Bioburn pelletizer. For the definition of good pellets see Table 1, Table 2, Figure 9 and Figure 10. Therefore, for each biowaste, quantities were increased (from 100% FS: 0% biowaste) until a poor pellet was produced. Thereafter a binder was added with increased percentage (starting from 0%).

Following identification of the FS to biowaste and binder ratio which produces good pellets (i.e. score of 2 or greater, see Table 1, Table 2, Figure 9 and Figure 10), sufficient quantities for gasification experiments were produced (approximately 120 kg dry basis). Following pelletizing, pellets were solar-dried in a storage area at NWSC Lubigi on drying racks and tarpaulins to < 12% moisture content suitable for gasification (see Figure 3, Figure 4 and Figure 5). After drying to < 12% moisture content, the pellets were packed in plastic sacks and transported to the Centre for Research in Energy and Energy Conservation (CREEC) at Makerere University for gasification experiments.

Figure 3: Drying of pellets

Figure 4: Tarpaulin with dried pellets and plastic bag for transportation

Figure 5: Racks for pellet drying.

Sample preparation

For pelletizing, dewatered FS was collected from full-scale drying beds at NWSC Lubigi (34 x 7 m) at a moisture content of approximately 45-64%. At NWSC Lubigi, the drying beds have roofs for rain protection. During the removal of the dewatered FS, care was taken to avoid removal of the sand filter layer with the sludge as this increases the ash content which is undesired for pelletizing (i.e. wearing off of the extruder) and energy recovery (Gold et al., submitted-b; Seck et al., 2015). Following removal of the dewatered FS from drying beds, in order to have a suitable particle size for pelletizing, FS was crushed to a size < 1 cm using a wooden rolling pin. According to Bioburn, less than 2 cm is a suitable size for pelletizing with their pelletizing technology (Studer, personal communication).

Byrne et al. (2015) identified most suitable biowastes for energy recovery in Kampala. Based on this assessment, in this study, FS was co-pelletized with sawdust, spent grain, coffee husk and banana peels (see Figure 6). Spent grain and banana peels have a high moisture content and were sun-dried in the storage areas at NWSC Lubigi to a moisture content of around 60% for pelletizing experiments (Byrne et al., 2015). Preliminary experiments identified that a binder might be necessary for certain biowastes to produce a pellet with quality parameters scored 2 or greater (see Table 1, Table 2, Figure 9 and Figure 10). In this study, waste cassava flour was used as a binder. Waste cassava flour is a waste produced during grounding of cassava in food industries. It is collected and sold for use. Potentially, waste cassava flour is a food source for low income communities. Therefore, in order to not compete with food production, the use of a binder for pelletizing should be kept to a minimum.

Sawdust

Coarse sawdust

Fine sawdust

Coffee husk

Spent grain

Banana peels

Figure 6: Biowastes used for co-pelletizing with faecal sludge in this study.

For the pelletizing trials, 10 kg batches of FS with biowastes and a binder (if required, see below) on wet weight basis were mixed. FS, biowastes and the binder were mixed by hand to a homogeneous sample for pelletizing. Material which could damage the pelletizer such as gravel or solid waste was removed manually. The homogenized sample was left for approximately 20 minutes for the sample to reach homogeneous moisture content. The same method was followed for the production of larger quantities of pellets for gasification.

Sample collection

Samples were collected from dewatered FS, biowastes, the binder and pellets. The entire FS, biowaste and binder volume was divided into four sections and one grab sample was collected from each pile. Sampling was done whenever a new batch of FS, biowaste or binder was used. Following sampling, FS, biowastes and the binder were stored in/under plastic sacks to avoid change of the moisture content between pelletizing trials. Pellets were collected in a plastic container. For sampling, the container was divided, by height into four equal sections and one grab sample was collected from each section. Dried pellets were collected by dividing the drying area (tarpaulin or drying rack) into six sections. From each section one grab sample was collected. Grab samples were compiled to one composite and transported to the laboratory for analysis the same day.

Pelletizing

Preliminary experiments with the Bioburn pelletizer demonstrated that the extruder requires pre-heating for good performance. Therefore, before pelletizing experiments, the pelletizer was operated with 100% FS for approximately ten minutes.

Figure 7 shows the hopper at the top of the Bioburn pelletizer. For pelletizing, the FS and biowaste mixture was placed into the hopper. Following, the mixture was homogenized by rotating shovels and pushed into the extruder for pelletizing. As shown in Figure 8, in the Bioburn pelletizer, the pellet leaves the extruder through a nozzle at the front. Preliminary experiments demonstrated that the entrance from the hopper to the extruder and from the extruder to the nozzle can clog when pelletizing biowastes with high moisture content greater than 60%. In these cases, pelletizing was stopped and the entrance to the extruder and the nozzle was cleared. Preliminary experiments also demonstrate that pelletizing bio-waste with a moisture content less than 30% results in the bio-waste shooting out of the extruders instead of producing pellets. The low moisture content in the biowaste causes over heating of the extruder.

Figure 7: Rotating shovels pushing the FS and biowaste mixture into the extruder.

Figure 8: Pellet leaving the extruder through the nozzle.

After a constant pellet production was established the production rate was measured. Production rate is the weight change of a bucket by ten minutes of pelletizing. During measurement of the production rate, the extruder speed was set to maximum and the cutter speed was adjusted for a pellet length of approximately four centimeter. The moisture content of the FS, biowaste and binder mixture (calculated based on the individual moisture contents and the quantity) were used to estimate the production rate on dry basis. The production rate was measured once for each 10 kg pelletizing trial and in triplicates during pelletizing for gasification.

$$PR_{wet} = \frac{\frac{W}{T} * 60}{1000} \ [kg/h]$$

$$PR_{TS} = (1 - MC_{mix}) * PR_{wet} \ [kg\ TS/h]$$

Weight of the pellets $[g]$	W
Time $[min]$	T
Production rate on wet basis $[kg/h]$	PR_{wet}
Production rate on dry basis $[kg\ dry\ mass/h]$	PR_{dry}
Moisture content of the mixture [%]	MC_{mix}

Scoring of pellet quality

Texture, strength, compactness and production rate of pellets were used in this study to compare the pellet quality of different FS, biowaste and binder mixtures. A short description of these parameters is included in Table 1. During pelletizing of each FS, biowaste and binder mixture a score was assigned for each parameter according to Table 2.

Table 1: Definition of the parameters used to quantify the pellet quality of different FS and biowaste mixtures.

Texture	Describes visually the appearance of the pellet surface. The surface varies between coarse and smooth as shown in Figure 9.
Strength	Describes the resistance of the pellet against breaking it in two pieces by hand. Strength is evaluated at <12% moisture content.
Compactness	Describes visually the increase of the pellet diameter after leaving the nozzle as shown in Figure 10.
Production rate	Described how many kilos of pellets are produced per hour on dry basis (kg dry mass/h). See Table 2.

Figure 9: Texture of two different pellets. The score (see Table 2) decreases from up (score 3), to down (score 1).

Figure 10: Compactness of three different pellets. The score (see Table 2) decreases from the left (score 3), to the right (score 2).

Table 2: Scoring system to compare pellet quality.

	Description	Score
Poor	texture, compactness, strength, production rate <10 kg dry mass/h	1
Good	texture, compactness, strength, production rate <10-20 kg dry mass/h	2
Very good	texture, compactness, strength, production rate >20 kg dry mass/h	3

Analysis

FS, biowastes and the binder were analyzed for moisture and ash content. Pellets were analyzed for moisture and ash content, calorific value and bulk density. Moisture content was determined gravimetrically at 105°C according to Standard Methods ((APHA), 2005). As this procedure is time consuming and therefore not suitable to monitor large-scale pellet production, results of moisture content analysis according to Standard Methods was compared with five commercial moisture meters (see Table 3). For this comparison, the moisture content of one pellet was measured in triplicate and the laboratory results compared to that of the five moisture meters respectively.

The moisture meters Voltcraft FM-300, Laserliner dampfinder, Moisture Detector MD, Dr. Meter® MD-812 LCD and Protimeter mini BLD200 had a moisture content range of 6-99%, 6-44%, 5-40% and 6-90% respectively for wood and building materials. Moisture Detector MD had a moisture content of 5-50% for wood and 1.5-33% for building materials.

Table 3: Product details for the five moisture meters used in this study.

Model and Retailer/manufacturer	Cost	Moisture content range
	USD	%
Voltcraft FM-300	108	6 - 99
Laserliner dampfinder	60	6 - 44
Moisture Detector MD	20	5 - 50 (wood) 1.5 - 33 (building materials)
Dr.Meter® MD-812 LCD	18	5 - 40
Protimeter mini BLD2000	200	6 - 90

Results and Discussion

Pelletizing trials

Table 4 shows the results from co-pelletizing of FS with sawdust. Pellets with quality parameters scored 2 or 3 (see Table 1, Table 2, Figure 9 and Figure 10) could be produced with FS quantities > 45% and binder of 5 to 10% (see trials marked in green and orange). Only at a FS quantity of 90% a quality pellet was produced without a binder. At sawdust concentrations > 45% poor pellets were produced (see trials marked in red). Byrne et al. (2015) reported ash contents for FS of 45%. In comparison, co-pelletizing of FS with sawdust reduced the ash content to 19% (see trial 2) which is more suitable for gasification. Sawdust pellets with parameters scored 2 or 3 could be produced with a quantity of 30% binder without mixing with FS. Fine sawdust produced pellets with score 1 without FS.

Table 4: Results from pelletizing trials of FS with sawdust. The mixture is presented in the order FS: coarse sawdust: sawdust: fine sawdust.

Trial	Unit	1	2	3	4	5	6
Mixture	% wet basis	40:0:50:0:10	45:0:22.5:22.5:10	50:0:0:40:10	50:0:20:20:10	50:0:40:0:10	55:0:40:0:5
Scoring	1-3	1:1:1:-	3:3:3:2	3:3:3:-	3:3:3:-	1:2:1:-	2:2:2:-
Moisture content	%	-	48.1*	-	-	-	-
Ash content	% dry basis	18.6**	19.0	22.6**	22.6**	22.6**	24.3**
Trial	**-**	**7**	**8**	**9**	**10**	**11**	**12**
Mixture	% wet basis	65:0:30:0:5	65:30:0:0:5	68:0:27:0:5	70:0:20:0:10	70:0:0:25:5	63:0:32:0:5
Scoring	1-3	2:3:2:1	1:1:1:-	3:3:3:-	3:3:3:-	3:3:3:2	3:2:2:-
Moisture content	%	45.1*	-	-	-	39.6*	-
Ash content	% dry basis	21.5	28.3**	29.5**	30.6**	30.3**	27.5**
Trial	**-**	**13**	**14**	**15**	**16**	**17**	**18**
Mixture	% wet basis	90:0:10:0:0	75:0:20:0:5	0:0:80:0:20	0:0:75:0:25	0:0:70:0:30	0:0:60:0:40
Scoring	1-3	3:2:3:-	3:3:3:-	1:1:1:-	1:1:1:-	2:2:2:2	2:3:2:1
Moisture content	%	-	-	49.8*	47.5*	45.2*	40.6*
Ash content	% dry basis	38.0**	32.3**	3.2**	3.5**	3.8**	4.4**
Trial	**-**	**19**	**20**	**21**	**22**	**23**	**24**
Mixture	% wet basis	0:0:50:0:50	0:0:0:70:30	0:0:0:80:20	0:0:0:90:10	0:0:0:95:5	0:0:0:100:0
Scoring	1-3	3:3:3:1	3:1:3:1	3:1:3:2	3:1:3:1	3:1:3:1	1:1:1:-
Moisture content	%	36.0*	53.6*	59.4*	65.2*	68.1*	71.0*
Ash content	% dry basis	5**	3.8**	3.2**	2.6**	2.3**	0.2**

*Calculated based on the moisture content and ratio of the respective FS, biowaste and binder.
**Calculated based on the ash content and ratio of the respective FS, biowaste and binder

Table 5 shows the results from co-pelletizing of FS with coffee husks. Pellets with FS quantities 50-70% and binder of 5 to 10% produced pellets scored 2 or greater (see trials marked in green and orange). Poor pellets were produced at coffee husk quantity > 80% (see trials marked in red). Co-pelletizing of FS with coffee husks reduced the ash content to 22% (see trial 8). Coffee husks pellets with parameters scored 2 or 3 (see Table 1, Table 2, Figure 9 and Figure 10) could be produced with 30 to 50% binder. However, they could not be cut mechanically by the pelletizer and were cut manually which is unsuitable for large-scale production.

Table 5: Results from pelletizing trials of FS with coffee husk. The mixture is presented in the order FS: coffee husk: waste cassava flour.

Trial	Unit	1	2	3	4	5	6	7	8
Mixture	% wet basis	80:20:0	75:20:5	70:25:5	68:25:7	65:30:5	63:30:7	60:30:10	53:40:7
Scoring	1-3	-:-:-:1	-:-:-:1	2:3:2:2	2:3:2:2	3:3:3:2	2:3:2:2	2:3:2:2	2:3:2:2
Moisture content	%	44.6*	42.7*	40.8*	35.7*	39.0*	38.2*	37.0*	34.5*
Ash content	% dry basis	-	-	-	-	-	-	-	22.0
Trial	-	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Mixture	% wet basis	50:40:10	0:100:0	0:95:5	0:90:10	0:80:20	0:70:30	0:60:40	0:50:50
Scoring	1-3	2:3:3:2	1:1:1:-	1:1:1:-	1:1:2:-	2:3:2:3	2:3:3:3	2:3:3:3	3:3:3:2
Moisture content	%	33.3*	27.0*	26.3*	25.6*	24.2*	22.8*	21.4*	20.0*
Ash content	% dry basis	-	-	-	-	-	-	-	-

*Calculated based on the moisture content of the respective biowaste and the ratios.

Table 6 shows the results from co-pelletizing of FS with spent grain. Pellets with parameter scores 2 or 3 could be produced with FS quantities up to 50% without the use of a binder. No spent grain quantity > 50% was tested. Co-pelletizing of FS reduced the ash content to 26% (see trial 3).

Table 6: Results from pelletizing trails of FS and spent grain. The mixture is presented in the order FS: spent grain.

Trial	Unit	1	2	3
Mixture	% wet basis	70:30	60:40	50:50
Scoring	1-3	3:3:3:2	3:3:3:2	3:3:3:2
Moisture content	%	52.2*	54.6*	57.0*
Ash content	% dry basis	30.0	28.0	26.0

*Calculated based on the moisture content of the respective biowaste and the ratios.

Table 7 shows the results from co-pelletizing of FS with banana peels. Pellets with parameter scores 2 or 3 could be produced without a binder at banana peels quantities < 40%. At lower FS quantities, 5 to 10% binder was required. Co-pelletizing of FS reduced the ash content to 22% (see trial 4).

Table 7: Results from pelletizing trials of FS, banana peels and waste cassava flour. The mixture is presented in the order FS: banana peels: waste cassava flour.

Trial	Unit	1	2	3	4
Mixture	% wet basis	70:30:0	60:40:0	55:40:5	50:40:10
Scoring	1-3	2:2:2:3	2:1:2:3	2:2:2:3	2:2:2:3
Moisture content	%	46.1*	42.8*	40.7*	38.5*
Ash content	% dry basis	28.0	25.0	23.0	22.0

*Calculated based on the moisture content of the respective biowaste and the ratios.

Results from co-pelletizing of FS with spent grain suggest that both FS and spent grain have binding properties. Therefore, FS was co-pelletized with sawdust, coffee husks and spent grain. The results are shown in Table 8 and demonstrate that coffee husk can be co-pelletized with FS and spent grain without waste cassava flour as a binder (trial 10). In contrast, co-pelletizing of FS, sawdust and spent grain produced poor pellets. This means that biowastes mixture needs to be assessed by simple pelletizing trials on a case-by-case basis.

Table 8: Results from pelletizing trails of FS, sawdust, coffee husk and spent grain. The mixture is presented in the order FS: sawdust: coffee husk: spent grain.

Trial	Unit	1	2	3	4	5
Mixture	% wet basis	70:20:0:10	70:10:0:20	70:0:20:10	60:30:0:10	60:10:0:30
Scoring	1-3	2:1:2:1	3:3:3:2	3:3:2:-	1:1:1:-	3:3:3:2
Moisture content	%	44.0*	46.9*	-	47.7*	48.5*
Ash content	% dry basis	-	-	28	-	-
Trial	**-**	**6**	**7**	**8**	**9**	**10**
Mixture	% wet basis	60:0:30:10	60:0:30:10	50:0:40:10	50:0:30:20	40:0:40:20
Scoring	1-3	2:2:2:-	1:1:1:2	3.3:2:-	3:3:2:-	3:3:3:-
Moisture content	%	-	44.1*	-	-	-
Ash content	% dry basis	25	-	28	21	21

*Calculated based on the moisture content of the respective biowastes and ratios.

Table 4 to Table 8 demonstrates that biowastes can be co-pelletized with FS to effectively reduce the ash content to 19%. In general, high biowaste quantities required high quantities of binder and produced poorer pellets. Poor pellet quality also meant operational problems such as engine shut down and blockages at the inlet and outlet to the extruder.

At high biowaste quantities waste cassava flour was required as a binder. Production of pellets with FS without a binder was only feasible with spent grain, spent grain/coffee husks or low biowaste quantities: < 10% for sawdust and < 30% for banana peels. As use of a binder is undesired (i.e. expensive, food for low income communities) this means that co-pelletizing of FS with spent grain, banana peels and spent grain/coffee husks is superior to sawdust. As banana peels have a high moisture content and high costs, pelletizing trials in this study identified spent grain and spent grain/coffee husks as the optimal biowaste for co-processing with FS to reduce the ash content of fuel pellets for gasification.

The results also demonstrate that similar FS, biowaste and binder mixtures produce different results. For example, as shown in Table 8, co-pelletizing of FS, coffee husks and spent grain at a ratio of 60%, 30% and 10% respectively produced pellets with parameter scores 2 or 3 in trial

6 and poor pellet in trial 7. This suggests that several biowaste characteristics and operational parameters influence the pelletizing performance such as moisture content and homogeneity, particle size, cutter and extruder speed and extruder temperature and wearing-off. A challenge throughout all experiments was to maintain the moisture content of the FS, biowaste and binder over several days.

Pelletizing for gasification

Based on the results from the pelletizing trials larger quantities of pellets were produced for gasification. The results are summarized in Table 9.

Table 9: Results of pelletizing of gasification experiments

	Ratio	Ratio	Moisture content	Ash content pellet	Calorific value	Bulk density	Scoring	Production rate
	% wet basis	% dry basis	%	% dry mass	MJ/kg dry basis	kg/m^3	1-3	kg dry basis/ h
FS	100:0:0	100:0:0	37*	41	9.85	653	3:3:3	15[2]
Fine sawdust	90:10:0	74:26:0	66*	4	17.04	240	3:1:3	7[2]
Sawdust	70:30:0	51:49:0	46*	4	16.92	172	2:1:2	7[2]
Coffee husk	90:10	88:12:0	26 *	8	16.06	346	3:1:3	19[2]
Spent grain	100:0:0	100:0:0	50	5	17.36	240	3:3:3	17[2]
FS: sawdust: binder	65:30:5	50:42:8	45*	21	17.4	333	2:3:2	7[2]
FS: coffee husk: binder	53:40:7	39:52:9	35*	21	15.6	556	2:3:2	19[2]
FS: fine sawdust: sawdust: binder	45:22.5: 22.5:10	34:10.5: 29.5:17	48*	19	14.0	333	3:3:3	9[2]
FS: coffee husk: spent grain	50:20:30	39:19:42	43*	22	16.4	444	3:3:2	16[2]
FS: spent grain	50:50:0	53:47:0	51*	27	15.8	518	3:3:3	18[2]

[2]Calculated with the equation for production rate on dry basis, see scoring of pellet quality.
*Calculated based on the moisture content of the respective biowastes and ratios.

In order to validate whether pellets are a fuel source for gasification or not (specifically for the Power Pallet produced by All Power Labs), sawdust, fine sawdust, coffee husks and spent grain were pelletized without FS as a control. Wood chips are a working fuel source for this technology. Pelletizing of sawdust and coffee husks produced poor pellets with frequent operational problems such as engine shut down and blockage of the extruder. Drying of sawdust pellets was a challenge as they were very fragile at low moisture contents. This means that pelletizing of these biowastes at large-scale for gasification or other energy recovery is not feasible.

Co-pelletizing of FS with sawdust and fine sawdust confirmed the results from the pelletizing trials. Co-pelletizing produced pellets with parameter scores of 2 and 3, reduced the ash content from 41% to 19-27% and increases the calorific value from 11.1±4.6 MJ/kg dry basis (Byrne et al., 2015; Gold et al., submitted-b) to 17.4 and 17.0 MJ/kg dry basis respectively. The bulk density was 333 kg/m^3. Co-pelletizing of FS with sawdust and fine sawdust produced better results compared to co-pelletizing with sawdust only. It appears that this is due to the additional texture when two different particle sizes are pelletized.

Co-pelletizing of FS with coffee husks confirmed the results from the pelletizing trials. Co-pelletizing reduced the ash content from 41% to 21% and increased the calorific value from 10.9 to 11.1 MJ/kg dry basis to 15.6 MJ/kg dry basis.

Co-pelletizing of FS with spent grain confirmed the results from the pelletizing trials. Co-pelletizing produced pellets with parameter scores 2 or 3 without the need for a binder. Co-pelletizing reduced the ash content of FS pellet from 41% to 27% and increased the calorific value 10.9 to 11.1 MJ/kg dry basis to 15.8 MJ/kg dry basis. During drying of spent grain pellets, both during pelletizing trials and pelletizing for gasification, pellets developed a growth of mold on them. Less mold was observed with a thinner layer on the drying racks. This mold formation is not a problem for gasification but should optimally be avoided.

Figure 11: Mold formed during drying on FS pellets co-pelletized with spent grain.

Moisture meters for monitoring of pellet drying

Figure 12 to Figure 16 show the deviation in moisture content between the five tested moisture meters and the laboratory moisture content results (ΔMC error) as a function of the laboratory moisture content results. In the following, the laboratory moisture content is considered as being the more accurate and precise measure. Further, a ΔMC error of < ±10% is considered as being acceptable for reliable monitoring of pellet moisture content.

In general, the results demonstrate that the moisture meters produce higher moisture content results compared to the laboratory results.

Figure 12 and Figure 13 show results of the Voltcraft FM-300 and Moisture Detector. These results demonstrate that the moisture content measured by the moisture meters have a ΔMC error < 10% only within a moisture content of approximately 0 to 15% whereas the ΔMC error increases at a moisture content > 15%. Only the Laserliner dampfinder maintained a ΔMC error < ±10% at moisture contents of 30% (see Figure 14). This means that moisture meters are a good approximation of the final moisture content of pellets for gasification but not for monitoring of the drying rate.

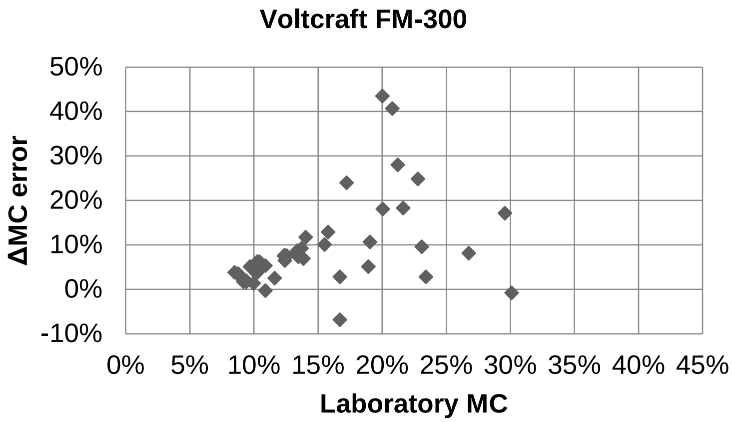

Figure 12: Deviation between moisture content results measured by the Voltcraft FM-300 versus laboratory results as a function of the laboratory moisture content results.

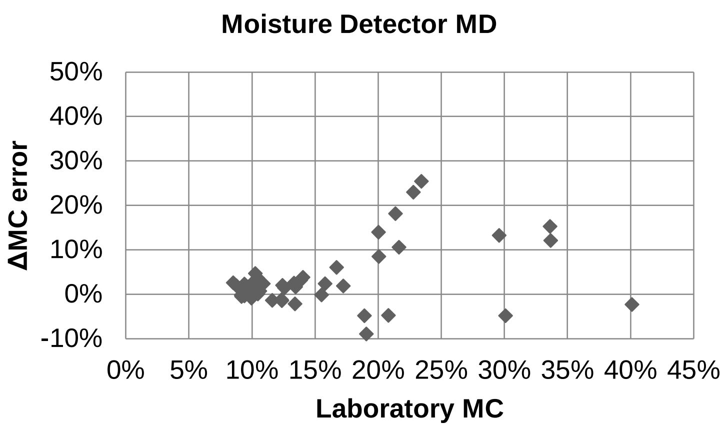

Figure 13: Deviation between moisture content results measured by the Moisture Detector MD versus laboratory results as a function of the laboratory moisture content results.

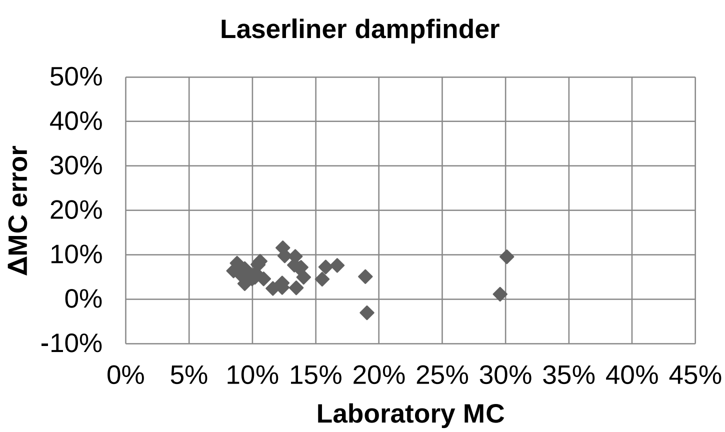

Figure 14: Deviation between moisture content results measured by the Laserliner dampfinder versus laboratory results as a function of the laboratory moisture content results.

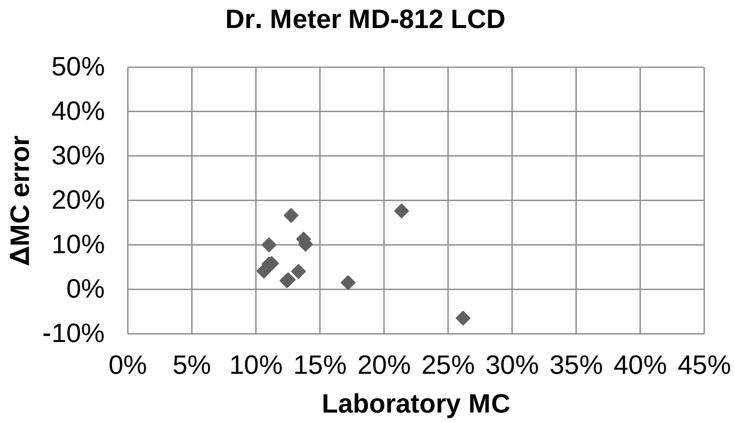

Figure 15: Deviation between moisture content results measured by the Dr. Meter MD812 LCD versus laboratory results as a function of the laboratory moisture content results.

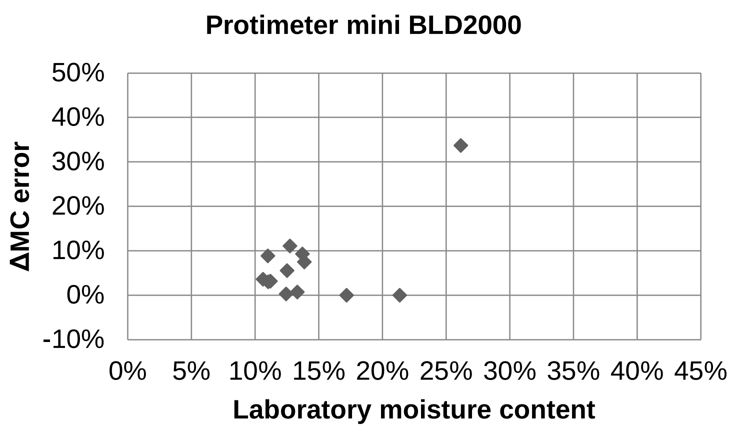

Figure 16: Deviation between moisture content results measured by the Protimeter mini BLD2000 versus laboratory results as a function of the laboratory moisture content results.

Table 10 shows the ΔMC error of all moisture meters between a laboratory moisture content of 0-15%. Within this range, the moisture detector MD which is the cheapest product produced the most accurate and precise results compared to the laboratory results and is further recommended for monitoring of the moisture content of dried FS pellets for gasification. In practice to ensure that the moisture content of the pellet is <12% for gasification, the errors included in Table 10 should be added to the moisture meter reading.

Table 10: Showing results for the whole moisture content range but also specified for up to 15% moisture content for the average error that the moisture meters show when given a reading.

	Voltcraft FM-300	**Laserliner dampfinder**	**Moisture detector MD**	**Dr. Meter MD-812 LCD**	**Protimeter mini BLD2000**
	ΔMC error	**ΔMC error**	**ΔMC error**	**ΔMC error**	**ΔMC error**
Average ΔMC error for 0-15% moisture content	5.0	6.1	1.3	7.1	5.3

Conclusions

This study demonstrated that banana peels, sawdust, coffee husk and spent grain can be co-pelletized with FS thereby increasing fuel quantities and the fuel quality (i.e. ash content) for resource recovery. Key findings include:

- Co-pelletizing of biowastes with FS produce pellets suitable for gasification.
- Spent grain and spent grain/coffee husks are optimal feedstocks for co-pelletizing considering pellet quality and production rate.
- FS, spent grain and low quantities of biowaste are most cost-effective feedstocks for production of pellets.
- A process of mixing/blending faecal sludge and biowaste needs to be included for successful co-pelletizing.
- Moisture meters are a reasonable proxy for pellet dryness between 0 to 15% moisture content.

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