Research Paper

Suitability of fecal sludge from composting toilets as feedstock for carbonization

Tobias Hübner, André Herrmann, Jörg Kretzschmar and Falk Harnisch

ABSTRACT

Composting toilets provide a promising decentralized alternative to sewer based sanitation systems. However, the valorization of fecal sludge from composting toilets (CFS) by conventional technologies is limited. In this study, we evaluated carbonization as an alternative valorization route for CFS, providing a time-efficient, decentral applicable and hygienically safe treatment option. CFS was carbonized using either pyrolysis (at 500 °C for 1 h) or hydrothermal carbonization (HTC, at 200 °C for 4 h). CFS exhibits promising feedstock characteristics, such as high total solids (TS, 21 ± 9%) and low ash content (9 ± 2%$_{TS}$). HTC of CFS exhibits high char yields (75 ± 7%) while pyrolysis char from CFS exhibits elevated higher heating values (25 ± 2 MJ kg^{-1}) and low ash content (24 ± 5%$_{TS}$) compared to chars produced from fecal sludge (FS) from other sources. Further calculations showed that FS with low TS amended with sawdust can be used as inexpensive feedstock to achieve energy self-sufficient pyrolysis operation.

Key words | bio-toilet, compost toilet, dry toilet, fecal sludge, hydrothermal carbonization, pyrolysis

Tobias Hübner (corresponding author)
Falk Harnisch
Helmholtz-Centre for Environmental Research
  GmbH – UFZ,
Department Environmental Microbiology,
  Permoserstraße 15, 04318 Leipzig,
Germany
E-mail: tobias.huebner@ufz.de

André Herrmann
Biorefinery Department,
DBFZ Deutsches Biomasseforschungszentrum
  gemeinnützige GmbH,
Torgauer Straße 116, 04347 Leipzig,
Germany

Jörg Kretzschmar
Biochemical Conversion Department,
DBFZ Deutsches Biomasseforschungszentrum
  gemeinnützige GmbH,
Torgauer Straße 116, 04347 Leipzig,
Germany

INTRODUCTION

Most people living in high-income countries have access to sewer-based sanitation, e.g. 95% of households in Germany (DSTATIS 2015). Sewer-based sanitation is based on well-established technologies enabling hygienically safe treatment of wastewater. Thereby its long-living infrastructure is based on high capital expenditure (capex) and requires high operational expenditures (opex), mainly for maintenance and electric energy. Due to their centralized structures most technologies are increasingly inefficient and almost unsuitable for sparsely populated regions, e.g. rural areas. Wastewater is increasingly considered as a resource, but the technological costs for nutrient recovery are high, because of their high dilution (Larsen et al. 2013; Anand & Apul 2014).

On-site sanitation is widespread in many low-income countries, e.g. 65–100% of urban areas in sub-Saharan Africa (Strauss et al. 2000). On-site sanitation has no need for a sewer system and commonly includes on-site collection (e.g. from pit latrines and septic tanks), transport (e.g. in trucks) and off-site treatment of the obtained fecal sludge (FS). However, due to insufficient decentralized sanitation infrastructure, FS often reaches the environment untreated causing environmental pollution as well as severe health problems (Strande et al. 2014).

Composting toilets, being also denominated as dry toilets or bio-toilets (Lopez Zavala & Funamizu 2006), are on-site sanitation facilities that are used as an alternative to centralized sewer-based sanitation systems. Composting toilets are operated waterless and typically sawdust is added for odor reduction and for facilitating a post-treatment by aerobic composting. Composting toilets provide the opportunity of being operated fully decentralized, reduce capex and opex for sanitation infrastructure, save water and may even produce a

valuable fertilizer. Thus, composting toilets are most commonly used in rural areas and in areas with water shortages (Anand & Apul 2014).

Fecal sludge from composting toilets (CFS) is typically treated by aerobic composting that allows for the stabilization, sanitization and reuse of the treated solids as fertilizer or soil conditioner (Anand & Apul 2014). However, aerobic composting requires several weeks to provide safely sanitized and fully stabilized compost, which induces the need for high reactor volumes or high demand of treatment space. Depending on the availability of treatment space and time, this can lead to high opex. Also, aerobic composting has to be performed under controlled conditions, e.g. frequent aeration and turning, to maintain process temperature levels leading to hygienically safe sanitation (Niwagaba *et al.* 2009; Germer *et al.* 2010; Sossou *et al.* 2014).

Carbonization, including hydrothermal carbonization (HTC) and pyrolysis, proved to be an effective method for the conversion of different types of biological sludge into high-quality char with a broad range of applications (Libra *et al.* 2011). Carbonization can provide safe sanitation within minutes or hours due to the high process temperatures (Feachem *et al.* 1981). During carbonization the feedstock volume is significantly reduced and char is produced. The economical valorization of the char can lead to an opex decrease of the entire sanitation process (Diener *et al.* 2014). Thus, carbonization can be considered as an alternative valorization technology for CFS, overcoming common challenges of aerobic composting.

Pyrolysis of FS from various sources has been subject to few studies in the past, including raw feces (Ward *et al.* 2014), solids from the settling chamber of a septic tank (Liu *et al.* 2014), FS from septic tanks and pit latrines (Gold *et al.* 2018) and sewage sludge from wastewater treatment plants (Bagreev *et al.* 2001; Inguanzo *et al.* 2002; Bridle & Pritchard 2004; Wang *et al.* 2012; Huang *et al.* 2017; Zhu *et al.* 2017). HTC of FS from various sources has also been investigated by several researchers, including primary sewage sludge from a settling tank of a wastewater treatment plant (Danso-Boateng *et al.* 2013, 2015), FS from a septic tank (McGaughy & Reza 2017) and raw feces and sewage sludge using microwave HTC (Afolabi *et al.* 2015; Afolabi & Sohail 2017). These studies demonstrated that FS is a promising feedstock for carbonization. FS char exhibits beneficial properties, making it a

high-value product that can be used, for example, as solid fuel, for soil enhancement, and for carbon sequestration (Gold *et al.* 2018). However, the use of CFS as feedstock, for either pyrolysis or HTC, has not been studied, so far.

The application of carbonization for sanitation of FS still faces challenges. HTC requires high pressure reactor and safety equipment, which induces high capex and opex. Also, HTC char has to be dewatered and dried, if used as solid fuel (Afolabi & Sohail 2017). Pyrolysis, conversely, requires a dry input material. Pyrolysis of sewage sludge with $\geq 50\%$ total solids (TS) in a single reactor assembly was reported (Gerber 2011). However, a sophisticated reactor design using screw or double-screw feeding or conveying is required (Zhu *et al.* 2017). FS that commonly exhibits TS contents $<50\%$ (Strauss *et al.* 2000; Semiyaga *et al.* 2017; Strande *et al.* 2018) has to be mechanically dewatered and dried before pyrolysis, which increases the energy demand of the process. One approach to decrease the high energy demand for pyrolysis is the direct combustion of pyrolysis gas and (non-condensed) liquid to provide process heat for drying and pyrolysis, as demonstrated by several authors (Wang *et al.* 2012; Liu *et al.* 2014). However, the feasibility of an energy self-sufficient process operation is limited by the feedstock properties, such as TS content, and the product properties, such as amount and calorific value of the pyrolysis gases and liquids.

The objective of this study was to investigate the suitability of CFS as feedstock for pyrolysis and HTC. We performed chemical analysis on CFS and on its carbonization products that were obtained at standard carbonization conditions (pyrolysis at 500 °C for 1 h and HTC at 200 °C for 4 h). Experimental feedstock and char characteristics were compared to the available literature data of FS. Furthermore, we investigated how the addition of sawdust (SD) to FS (as typical for CFS) influences the energy balance of a model pyrolysis process. By addition of SD, TS and chemical oxygen demand (COD) of the input to the pyrolysis process increases and, in turn, the required energy for drying per kg of feedstock decreases. Thus, the aim was to demonstrate that SD addition can be used as an inexpensive method to achieve energy self-sufficient pyrolysis operation when using FS with low TS as feedstock. As an advantageous side-effect, the addition of SD before sludge drying was also shown to enhance drying performance because of an increased heat exchange capacity and an increased bed volume (Li *et al.* 2016), which

consequently decreases the required drying reactor capacity. It has also been demonstrated that the char surface area increases with the addition of SD before pyrolysis of different types of biological sludge, such as sewage sludge (Huang *et al.* 2017) or anaerobically digested pig manure (Troy *et al.* 2012), adding value to the char.

MATERIAL AND METHODS

Materials

CFS samples were collected from six different composting toilets (Ökolocus/Goldeimer, Germany). Three of these toilets were operated on a household scale with 4–10 frequent users over a period of six months from May to October 2016, in Germany. The other three toilets were operated at music festivals in Germany with an unknown number of users over a period of 5 days in July and August 2016, respectively. One of the sample toilets used direct urine diversion, while the other five toilets were operated with liquid drainage, i.e. urine and feces were mixed in the collection chamber and excess liquid was drained through a hole at the bottom of the container. Softwood sawdust was used as bulking material and toilet paper was added by the users. Each toilet was sampled once after operation. Therefore the toilet content was completely emptied, manually mixed with a shovel in a pile and then equally distributed on a tarpaulin. Five equivolumetric samples of approximately 600 g were randomly taken from different parts of the tarpaulin and merged to a full sample. The samples were stored at −18 °C prior to the experiments.

Pyrolysis and hydrothermal carbonization

Pyrolysis and HTC were performed using the three samples from household scale CFS.

For CFS pyrolysis 500 g of each tested sample was dried for 24 h at 105 °C, yielding between 100 and 150 g dried sample. Pyrolysis was performed in a muffle furnace (XCHAMB 1,280 by XERION, Germany) using an aliquot of 70 g of the dried sample in one repetition. The muffle furnace was heated at a rate of 8 °C min^{-1} from ambient temperature to 500 °C and the temperature was held for

1 h. The pyrolysis furnace was purged with N_2 during the entire operation. Purging started 30 minutes prior to the experiments.

HTC was performed in a 500 mL stirred autoclave (BR-300, Berghof Products + Instruments, Germany using a BTC 3,000 control panel) at 200 °C for 4 h with each sample in one repetition; 375 g of sample was used per experimental run according to the holding capacity of the reactor. All samples with TS concentrations higher than 20% were diluted to 20% TS with deionized water to guarantee proper mixing of the samples by the stirrer (range of TS of the used samples: 6.6–28%). After the HTC reactor cooled down to ambient temperature the produced chars were pressure filtered using a vacuum pump and MN 615 paper filters (12 μm pore size, by Marcherey-Nagel, Germany). The filter cake was subsequently dried at 105 °C for 24 h before analysis.

The tested combinations of temperature and reaction time for pyrolysis and HTC represent average reaction conditions that are commonly used in literature (Libra *et al.* 2011). In our case, all studies that used fecal sludge as feedstock for pyrolysis or HTC applied either of these reaction conditions (Danso-Boateng *et al.* 2013, 2015; Liu *et al.* 2014; Ward *et al.* 2014; Afolabi *et al.* 2015; Afolabi & Sohail 2017; Gold *et al.* 2018), thus, allowing for good comparison of our results with those from literature.

The experimental char yield Y (in %) was calculated by Equation (1):

$$Y = \frac{m_{char,TS}}{m_{CFS,TS}} \cdot 100\% \tag{1}$$

where $m_{char,TS}$ (kg) is the mass of produced char TS and $m_{CFS,TS}$ (kg) is the mass of CFS TS used in the experiment.

Analysis

CFS samples and gained char samples were analyzed for TS, ash, C (carbon), H (hydrogen), N (nitrogen), S (sulfur) and higher heating value (HHV). CFS was additionally analyzed for volatile solids (VS).

TS (in %) was calculated by Equation (2):

$$TS = \frac{m_{sample,TS}}{m_{sample}} \cdot 100\% \tag{2}$$

where $m_{sample,TS}$ (kg) is the mass of sample remaining after drying for 24 h at 105 °C in a drying oven (ED 400, Binder, Germany) and m_{sample} (kg) is the initial mass of the sample.

Moisture (in %) was calculated by Equation (3):

$$moisture = \frac{m_{sample} - m_{sample,TS}}{m_{sample}} \cdot 100\% = 100\% - TS \qquad (3)$$

VS (in %$_{TS}$) and ash content (in %$_{TS}$) were calculated by the following equations, respectively:

$$VS = \frac{m_{sample,VS}}{m_{sample,TS}} \cdot 100\% \qquad (4)$$

$$ash = \frac{m_{sample,ash}}{m_{sample,TS}} \cdot 100\% \qquad (5)$$

where $m_{sample,VS}$ (kg) is the mass of sample remaining after incineration at 550 °C and $m_{sample,ash}$ (kg) is the mass of sample remaining after incineration at 815 °C.

The ratios of SD to FS were calculated on the basis of the wet mass ($X_{SD/FS}$) and on the basis of the dry mass ($X_{SD/FS,TS}$) using the following equations, respectively:

$$X_{SD/FS} = \frac{m_{SD}}{m_{FS}} \qquad (6)$$

$$X_{SD/FS,TS} = \frac{m_{SD,TS}}{m_{FS,TS}} = \frac{TS_{SD}}{TS_{FS}} X_{SD/FS} \qquad (7)$$

m_{SD} (kg) and m_{FS} (kg) are the masses of wet SD and FS, $m_{SD,TS}$ (kg) and $m_{FS,TS}$ (kg) are the masses of SD and FS TS, respectively. TS_{SD} (%) and TS_{FS} (%) are the TS contents of SD and FS, respectively.

COD (in g_{O2} kg_{wet}^{-1}) was calculated based on the elemental composition:

$$COD = \frac{1}{100\%}$$
$$\left(\frac{C}{12 \ (g/mol)} + \frac{0.25 \ H}{1 \ (g/mol)} - \frac{0.75 \ N}{14 \ (g/mol)} - \frac{0.5 \ O}{16 \ (g/mol)} \right)$$
$$\times 32 \ \frac{g_{O_2}}{mol} * \frac{TS}{100\%} \qquad (8)$$

where C, H and N (%$_{TS}$) are contents of carbon, hydrogen and nitrogen measured by elemental analysis using an elemental analyzer (vario Macro cube, Elementar Analysensysteme GmbH, Germany) and O (%$_{TS}$) is the content of oxygen calculated by the difference to 100% (taking into account C, H, N and *ash*).

HHV of CFS and char samples were measured using a calorimeter (6400 Automatic Isoperibol Calorimeter by Parr Instrument GmbH, Germany).

Calculation of pyrolysis mass and energy balance

Mass and energy balances for a model pyrolysis process of CFS (Figure 1) were calculated. As feedstock CFS was assumed to be a mixture of FS and SD. For the calculations we used literature data as a basis, taking into account data of FS, sewage sludge (if data on FS were unavailable) and SD.

The mass balance was calculated according to Equation (9):

$$m_{CFS} = m_{vapor} + m_{off\text{-}gas} + m_{char} \qquad (9)$$

where m_{CFS} (kg), m_{vapor} (kg), $m_{off\text{-}gas}$ (kg) and m_{char} (kg) are the masses of the feedstock CFS (FS and SD on a wet basis), vapor
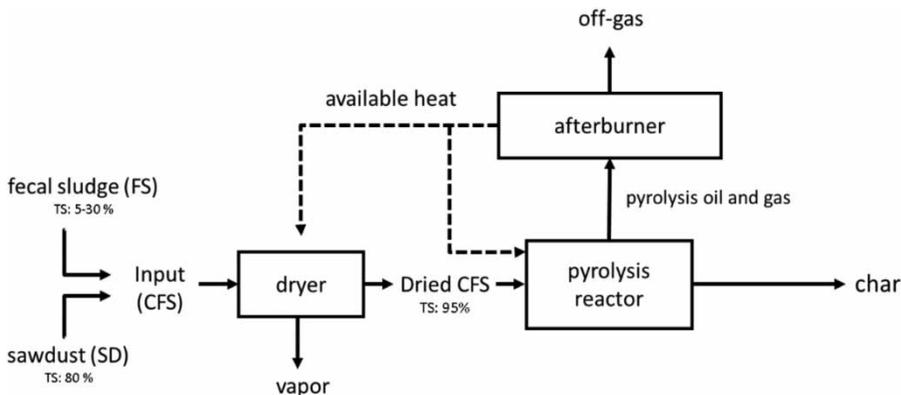

Figure 1 │ Reaction scheme of the investigated model pyrolysis process of CFS.

produced by the dryer, off-gas from pyrolysis oil and gas burning and produced char, respectively.

Energy for pyrolysis and drying was provided by exploiting the off-heat from direct burning of pyrolysis gases and oils (Wang *et al.* 2012; Liu *et al.* 2014). Energy self-sufficient operation was assumed to be achieved when the heat available from burning of pyrolysis oil and gas ($Q_{available}$) was equal to the heat required for drying (Q_{drying}) and pyrolysis ($Q_{pyrolysis}$):

$$Q_{available} = Q_{drying} + Q_{pyrolysis} \tag{10}$$

With

$$
\begin{aligned}
Q_{drying} &= \frac{1}{\eta_{dryer}}[m_{CFS,H_2O}c_{p,H_2O}(T_{dr}-T_{amb}) + m_{vapor}\Delta H_{v,H_2O} \\
&\quad + m_{CFS,TS}c_{p,CFS,TS}(T_{dr}-T_{amb})] \\
&= \frac{1}{\eta_{dryer}}m_{CFS}\left[\left(1-\frac{TS'_{CFS}}{100\%}\right)c_{p,H_2O}(T_{dr}-T_{amb})\right. \\
&\quad \left. +\left(1-\frac{TS'_{CFS}}{TS_{CFS,dried}}\right)\Delta H_{v,H_2O} + \frac{TS'_{CFS}}{100\%}c_{p,CFS,TS}(T_{dr}-T_{amb})\right]
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
Q_{pyrolysis} &= \frac{1}{\eta_{pyrolysis}}[m_{CFS,dried,H2O}\,c_{p,H_2O(vapor)}(T_{py}-T_{dr}) \\
&\quad + m_{CFS,TS}c_{p,CFS,TS}(T_{py}-T_{dr})] + \Delta Q_{pyrolysis} \\
&= \frac{1}{\eta_{pyrolysis}}m_{input} \\
&\quad \left[\frac{TS'_{CFS}}{TS_{CFS,dried}}\left(1-\frac{TS_{CFS,dried}}{100\%}\right)c_{p,H_2O(vapor)}(T_{py}-T_{dr})\right] \\
&\quad + \frac{TS'_{CFS}}{100\%}c_{p,CFS,TS}(T_{py}-T_{dr}) + \Delta Q_{pyrolysis}
\end{aligned}
\tag{12}
$$

Heat losses were taken into account by applying thermal efficiencies to the dryer η_{dryer} (−) (belt dryer: 70% (Arlabosse *et al.* 2011; Li *et al.* 2016)) and to the pyrolysis reactor $\eta_{pyrolysis}$ (−) (50% (Liu *et al.* 2014)), respectively. m_{CFS}, m_{CFS,H_2O}, m_{vapor}, $m_{CFS,TS}$, and $m_{CFS,dried}$ (kg) are the mass of feedstock CFS (FS and SD on a wet basis), the mass of water contained in the CFS, mass of water evaporated by the dryer, mass of total solids in the CFS and mass of water retained in the material after drying, respectively. T_{dr}, T_{py} and T_{amb} are drying temperature (150 °C), pyrolysis temperature (300–600 °C) and ambient temperature (20 °C), respectively. c_{p,H_2O} (4.167 kJ kg^{-1} K^{-1}), $c_{p,CFS,TS}$ (1.2 kJ kg^{-1} K^{-1} (Liu *et al.* 2014)) and $c_{p,H_2O}(vapor)$ (2.08 kJ kg^{-1} K^{-1}) are the specific heat capacities of liquid water, of the CFS TS and of water

vapor, respectively. $\Delta H_{v,H_2O}$ (2.26 MJ kg^{-1}) is the vaporization heat of water. $\Delta Q_{pyrolysis}$ (kJ) is the total reaction heat of pyrolysis. Values for heat of reaction of pyrolysis of FS were adapted from values of sewage sludge pyrolysis (Wang *et al.* 2012). Values for heat of reaction of SD were neglected. We accepted these inaccuracies and assumed them to be marginal because our results and also results of others (Wang *et al.* 2012; Liu *et al.* 2014) showed that heat of reaction of pyrolysis had only a very minor effect on the overall energy balance. TS_{CFS}' and $TS_{CFS,dried}$ (%) are the TS of the feedstock CFS before and after drying, respectively. TS_{CFS}' was calculated according to the fractions of FS and SD in the feedstock mixture as follows:

$$TS'_{CFS} = \frac{TS_{FS} + TS_{SD}X_{SD/FS}}{1 + X_{SD/FS}} \tag{13}$$

where TS_{FS} (%) are the total solids of FS and TS_{SD} (%) are the total solids of SD. We assumed a variation of TS_{FS} between 5 and 30%, a constant TS_{SD} of 20%, and constant $TS_{CFS,dried}$ of 95%.

The available heat from burning of pyrolysis oil and gas $Q_{available}$ was calculated by Equation (14). Heat losses were taken into account by applying a thermal efficiency η_{burner} (−) to the afterburner (85% (Wang *et al.* 2012)):

$$Q_{available} = \eta_{burner}Q_{pyrolysis\,oil/gas} \tag{14}$$

The accurate calorific value of pyrolysis oil and gas could not be measured in this study. Their energy contents were estimated from the closed energy balance of the pyrolysis, taking into account the chemically bound energy of the dried CFS ($Q_{CFS,TS}$), the energy introduced from the afterburner for pyrolysis heating ($\eta_{pyrolysis}Q_{pyrolysis}$), the chemically bound energy in the char ($Q_{char,chem}$) and heat contained by the hot char ($Q_{char,therm}$):

$$
\begin{aligned}
Q_{pyrolysis\,oil/gas} &= Q_{CFS,TS} + \eta_{pyrolysis}Q_{pyrolysis} \\
&\quad - Q_{char,chem} - Q_{char,therm} \\
&= m_{FS,TS}HHV_{FS} + m_{SD,TS}HHV_{SD} \\
&\quad + \eta_{pyrolysis}Q_{pyrolysis} - m_{char,TS}(HHV'_{char}+c_{p,char}(T_{py}-T_{amb})) \\
&= \frac{TS'_{CFS}}{100\%}m_{CFS}\left[\frac{HHV_{FS}+X_{SD/FS,TS}\,HHV_{SD}}{1+X_{SD/FS,TS}}\right. \\
&\quad \left. -\frac{Y'_{char}}{100\%}(HHV'_{char}+c_{p,char}(T_{py}-T_{amb}))\right] + \eta_{pyrolysis}Q_{pyrolysis}
\end{aligned}
\tag{15}
$$

$m_{SD,TS}$ (kg), $m_{FS,TS}$ (kg) and $m_{char,TS}$ (kg) are the masses of SD total solids and FS total solids in the feedstock CFS and produced char total solids, respectively. The HHV of FS (HHV_{FS}) was assumed as 18.1 MJ kg^{-1} (Liu *et al.* 2014), the HHV of SD (HHV_{SD}) as 19.6 MJ kg^{-1} (Owens & Cooley 2013; Li *et al.* 2016; Ronewicz *et al.* 2017). $X_{SD/FS,TS}$ was calculated by Equation (7) and $Q_{pyrolysis}$ according to Equation (12). Pyrolysis of FS and SD were assumed as parallel occurring processes (neglecting possible synergistic effects). Thus, char yield Y_{CFS}' (%) and $HHV_{CFS,char}'$ (MJ kg^{-1}) were calculated according to the fractions of FS and SD in the CFS feedstock mixture, as follows:

$$Y_{CFS}' = \frac{Y_{FS} + Y_{SD}X_{SD/FS, TS}}{1 + X_{SD/FS, TS}} \tag{16}$$

$$HHV_{CFS, char}' = \frac{HHV_{FS,char}Y_{FS} + HHV_{SD,char}Y_{SD}X_{SD/FS, TS}}{Y_{FS} + Y_{SD}X_{SD/FS, TS}} \tag{17}$$

where Y_{FS} (%) is the char yield from FS pyrolysis obtained from interpolation of literature values of Liu *et al.* (2014), Y_{SD} (%) is the char yield from SD pyrolysis calculated by interpolation of literature values from pine wood by Ronsse *et al.* (2013). $HHV_{FS,char}$ (MJ kg^{-1}) is the HHV of FS char obtained by interpolation of data from Ward *et al.* (2014) and $HHV_{SD,char}$ (MJ kg^{-1}) is the HHV of SD char (pine wood) calculated by interpolation of literature values from Ronewicz *et al.* (2017).

All performed interpolations can be found in the E-supplementary data of this work in the online version of the paper.

RESULTS AND DISCUSSION

Characteristics of fecal sludge from composting toilets

The analyzed CFS exhibited a TS of $21 \pm 9\%$, a VS of $90 \pm 3\%_{TS}$ and an ash content of $9 \pm 3\%_{TS}$ (Table 1). Measured carbon (C) and nitrogen (N) contents of CFS were $48 \pm 2\%_{TS}$ and $2.3 \pm 1.1\%_{TS}$, respectively, measured COD was 290 ± 135 g kg$^{-1}_{wet}$. These characteristics differ from those of FS, which possess lower TS (<20%), VS

Table 1 | Characteristics of CFS analyzed in this study and comparison to literature data of FS

		CFS (this study)[h]	FS (literature)				
			Pit latrine (lined)[c]	Septic tank[d]	Septic tank (Germany)[e]	Chemical toilet[e]	Primary sewage sludge[f]
Total solids (TS)	%	21 ± 9	5 ± 3	1–7	0.5–5	1–20	5–10
Moisture	%	79 ± 9	92 ± 2	93–99	95–99.5	80–99	90–95
Volatile solids (VS)	%$_{TS}$	90 ± 3	64 ± 12	50–73	–	–	60–80
Ash content	%$_{TS}$	9 ± 2^{h}	34 ± 21	–	–	–	25
Carbon (C), total	%$_{TS}$	48 ± 2	–	–	–	–	40
Hydrogen (H), total	%$_{TS}$	6.1 ± 0.3	–	–	–	–	5.4
Sulfur (S), total	%$_{TS}$	0.27 ± 0.06	–	–	–	–	1.6
Nitrogen (N), total	%$_{TS}$	2.3 ± 1.1	–	–	–	–	4.0
	g L^{-1}	17 ± 7^{a}	–	0.2–0.3	0.2–1.2	2–7	–
Chemical oxygen demand (COD)[g]	g L^{-1}	$291 \pm 135^{a,b}$	65 ± 44	7.8–43.0	2–60	4–90	–
HHV	MJ kg^{-1}	20.2 ± 2.3	–	–	–	–	–

[a]Unit g kg$^{-1}_{wet}$.
[b]Calculated from elemental composition.
[c]Semiyaga *et al.* (2017).
[d]Heinss *et al.* (1998) and Strande *et al.* (2018).
[e]ATV-Merkblatt 270 (1997).
[f]Libra *et al.* (2011).
[g]Calculated by Equation (8).
[h]$n = 6$, except for HHV measurement where $n = 3$.

($<80\%_{TS}$) and COD ($<100\,g\,L^{-1}$), along with higher ash content ($>10\%_{TS}$). The measured HHV of CFS was $20.2 \pm 2.3\,MJ\,kg^{-1}$, and thus, slightly higher than that of pure feces which are reported to be around $17\,MJ\,kg^{-1}$ (Rose *et al.* 2015).

We presume that the addition of SD and the solid-liquid separation in CFS are the main reasons for these deviations. SD contributes to the increased TS because of its own high TS (Ronewicz *et al.* 2017) and liquid separation leads to the additional loss of water. In turn, the high TS of CFS leads to an increase of COD and N concentration per wet mass, due to the increased amount of solids per kg. With SD addition in CFS, VS also increases and ash content decreases compared to FS, because of the high fraction of organic matter contained in SD (ash content SD: $0.1–8\%_{TS}$ (Libra *et al.* 2011) compared to ash content of pure feces with $7.5–16\%_{TS}$ (Rose *et al.* 2015)). Microbial degradation during settling and storage of the materials in the toilets will also alter the chemical composition, in particular, a decrease of VS and COD and increase of ash content can be expected (Libra *et al.* 2011). SD addition causes porous bulking of CFS during storage, thus fostering aerobic degradation of the material. Conversely, FS forms a liquid–solid suspension (Strande *et al.* 2014) and is thus expected to predominantly undergo anaerobic degradation during storage.

Characteristics pyrolysis and hydrothermal carbonization chars

Char that was produced by pyrolysis of CFS in this study exhibited an ash content of $24 \pm 5\%_{TS}$, which is considerably higher than the ash content of FS-derived pyrolysis char ($>37\%_{TS}$) (Table 2). This is most likely related to the comparably low ash content of CFS ($9 \pm 3\%_{TS}$) and the high ash content of FS ($34 \pm 21\%_{TS}$). The low ash content of CFS char indicates a high organic content, which explains the comparatively high C ($64 \pm 5\%_{TS}$) and N ($2.9 \pm 1.4\%_{TS}$) contents, high HHV ($24.3 \pm 1.9\,MJ\,kg^{-1}$) and low char yield ($32.6 \pm 2.6\%$). C and N account for $84.0 \pm 0.5\%_{TS}$ and $3.9 \pm 1.9\%_{TS}$, respectively, when calculated on an ash-free basis being well in line with values of $80–85\%_{TS}$ and $4–8\%_{TS}$ calculated from the literature values of FS chars, respectively (Liu *et al.* 2014; Ward *et al.* 2014; Gold *et al.* 2018). The

Table 2 | Characteristics of chars produced from CFS by pyrolysis and HTC in this study and comparison to literature data of chars produced from FS

		Pyrolysis char		HTC char	
		CFS (this study)	FS (literature)[a]	CFS (this study)	FS (literature)[b]
TS	%		–	25 ± 4[c]	–
Ash	$\%_{TS}$	24 ± 5	37–67	22 ± 12	25–36
C	$\%_{TS}$	64 ± 5	27–51	57 ± 5	38–49
H	$\%_{TS}$	2.1 ± 0.1	–	6.4 ± 0.7	5.4–6.6
N	$\%_{TS}$	2.9 ± 1.4	1.6–4.8	2.7 ± 0.8	0.9–3.0
S	$\%_{TS}$	0.6 ± 0.4	–	0.3 ± 0.1	–
O[d]	$\%_{TS}$	6.6 ± 1.4	–	15 ± 14	49–54
HHV	$MJ\,kg^{-1}$	24.3 ± 1.9	9–18	22.9 ± 2.4	18.5–25.0
Yield	%	32.6 ± 2.6	29–61	75.3 ± 6.9	39–67

[a]Liu *et al.* (2014), Ward *et al.* (2014) and Gold *et al.* (2018) pyrolysis conditions: 450–500 °C, 20–120 min.
[b]Danso-Boateng *et al.* (2013, 2015) and Afolabi *et al.* (2015) HTC conditions: 200 °C, 30–240 min.
[c]Measured after pressure filtration.
[d]Calculated by difference.

relatively low yield of CFS char is attributed to SD addition and, hence, the low ash content of the feedstock. This can be expected, as during pyrolysis inorganic compounds remain in the char, while organic compounds are partly volatized (Vreugdenhil & Zwart 2009; Libra *et al.* 2011). When applying similar pyrolysis conditions to SD, even lower char yields of around 25–30% were shown (Yan *et al.* 2011; Ronsse *et al.* 2013), which also supports the aforementioned reasoning. A decrease of char yield with addition of SD to sewage sludge was also demonstrated by Troy *et al.* (2012) and Huang *et al.* (2017). The HHVs of the here gained CFS-derived pyrolysis chars ($24.3 \pm 1.9\,MJ\,kg^{-1}$) are considerably higher than the literature values of FS chars (9–18 $MJ\,kg^{-1}$). This, again, can be related to the high organic content of CFS-derived pyrolysis char (indicated by its low ash content) as well as to the variation of feedstock compositions between FS and CFS. HHV values reported by other authors of, for example, $17.9 \pm 0.3\,MJ\,kg^{-1}$ (Ward *et al.* 2014) and $9.1 \pm 1.0\,MJ\,kg^{-1}$ (Gold *et al.* 2018) are gained from chars with ash contents of 37 and 67%, respectively.

When using HTC on CFS the produced char exhibited an ash content of $22 \pm 12\%_{TS}$ and C and N contents of 57 ± 5 and $2.7 \pm 0.8\%_{TS}$, respectively. In comparison to the literature the ash content of FS HTC char is slightly higher

($25\text{--}36\%_{TS}$), and C content is lower ($38\text{--}49\%_{TS}$) (Table 2). The HHV of CFS-derived by HTC char was $22.9 \pm 2.4 \text{ MJ kg}^{-1}$ and is, thus, in the range of FS-derived HTC chars ($18.5\text{--}25.0 \text{ MJ kg}^{-1}$). The comparatively high HTC yield of CFS char ($75.3 \pm 6.9\%$) can be attributed, again, to the addition of SD. Zhang *et al.* (2017) observed a considerable increase of HTC char yield when increasing the amount of SD in a sewage sludge–sawdust mixture used as feedstock for HTC. The moderate fluctuations of the observed yields from CFS HTC chars may be explained by the different composition of the used FS samples, for instance by different amounts of SD or different period of storage before experiment. Also the unequal TS concentrations of the tested samples may have had an impact on the HTC char yield, as low TS were shown to slightly decrease char yield in HTC of FS (Danso-Boateng *et al.* 2013).

Pyrolysis mass and energy balance

Influence of sawdust addition

Figure 2(a) shows the calculated ratio of SD to FS on a wet basis $X_{SD/FS}$ (Equation (6)) that is required to achieve energy self-sufficient operation at varying FS TS (TS_{FS}). Without the addition of SD ($X_{SD/FS} = 0$), energy self-sufficient operation is achieved at pyrolysis temperatures of $\geq 500\,°\text{C}$ and at $TS_{FS} \geq 30\%$. At pyrolysis temperatures of $<500\,°\text{C}$ TS_{FS} would have to be even higher to achieve energy self-sufficiency. As FS with a TS $> 20\%$ is unlikely to be found in practice (Table 1), energy self-sufficient operation without SD addition is not possible. Liu *et al.* (2014) calculated energy self-sufficient process operation using FS from the settling chamber of a septic tank. They used a similar process scheme and assumptions for their
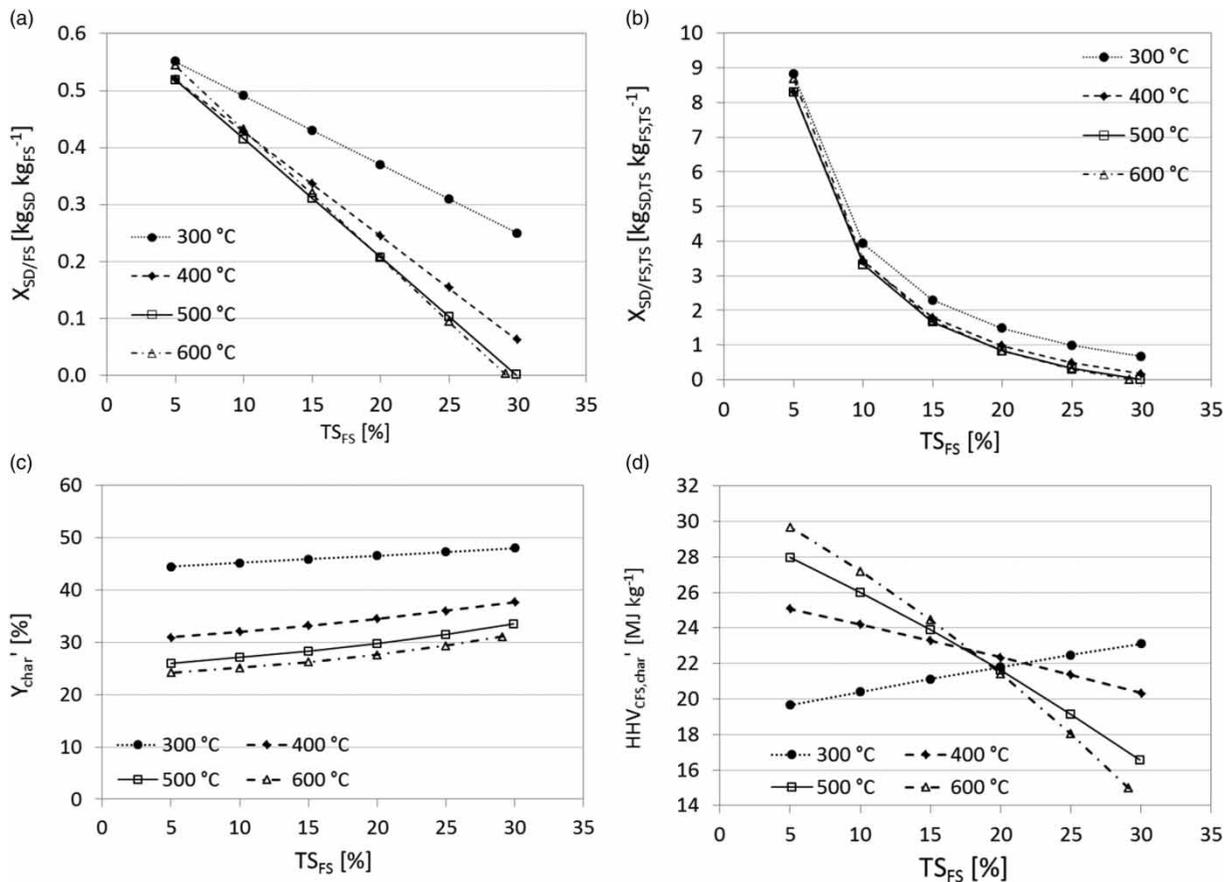
Figure 2 │ Results of process calculations for pyrolysis using CFS as feedstock assumed as mixture of fecal sludge (FS) and sawdust (SD): (a) and (b) show the sawdust to FS ratios on a wet basis ($X_{SD/FS}$) and on a dry basis ($X_{SD/FS,TS}$) required for energy self-sufficient operation at increasing FS TS (TS_{FS}) and at different pyrolysis temperatures, respectively; (c) shows char yield (Y_{CFS}') and (d) shows char HHV ($HHV_{CFS,char}'$) from CFS pyrolysis obtained under energy self-sufficient operation against TS_{FS} and at different pyrolysis temperatures, respectively.

investigation and calculated that TS_{FS} must be $\geq 43\%$ at 550 °C pyrolysis temperature to achieve energy self-sufficient operation. This TS_{FS} is even higher than the values derived in this study ($TS_{FS} \geq 30\%$ at 500 and 600 °C) and supports the aforementioned presumption.

With decreasing TS_{FS} energy self-sufficient operation can be achieved by the addition of SD which increases $X_{SD/FS}$ (Figure 2(a)). The rate at which $X_{SD/FS}$ has to increase with decreasing TS_{FS} varies among the different pyrolysis temperatures, as reflected by the inclinations of the graphs. Above 400 °C pyrolysis temperature has a small influence and above 500 °C its influence is negligible. However, the pyrolysis temperature has a high influence at 300 °C, as a considerably higher $X_{SD/FS}$ is required than at higher pyrolysis temperatures. These observations can be explained by the decrease of the solid product fraction (i.e. char) with increasing pyrolysis temperature (Figure 2(c)), which in turn causes an increase of the gaseous and liquid product fractions. Thus, more energy for process heating is available from burning of pyrolysis liquids and gases. Above 500 °C no influence of $X_{SD/FS}$ is observed, corresponding to very little changes in the distribution of the products above these temperatures (Ronsse *et al.* 2013; Liu *et al.* 2014). At the lowest investigated TS_{FS} of 5%, circa 0.55 $\text{kg}_{SD,wet}\ kg_{FS,wet}^{-1}$ have to be added to achieve energy self-sufficient operation regardless of pyrolysis temperature.

In Figure 2(b), $X_{SD/FS,TS}$ (Equation (7)) required for energy self-sufficient operation was plotted over varying TS_{FS} to demonstrate the fraction of total solids in the char that are derived from SD and from FS, respectively. The graphs demonstrate that at decreasing TS_{FS}, $X_{SD/FS,TS}$ has to increase exponentially. For example, at 5% TS_{FS} an $X_{SD/FS}$ of 0.55 (Figure 2(a)) corresponds to an $X_{SD/FS,TS}$ of around 8.5 (Figure 2(b)). Thus, circa 85% of TS of the char is derived from SD and only circa 15% of the char TS originates from FS. This clearly illustrates that when using FS with low TS as feedstock the gained CFS char will be predominantly SD-derived at energy self-sufficient operating conditions.

Calculated char yield and char higher heating value

As shown in Figure 2(c), Y_{CFS}' increases with an increasing TS_{FS} under energy self-sufficient operation. These observations can be expected and are related to the fact that we assumed Y_{CFS}' as the sum of Y_{SD} and Y_{FS} (Equation (16)). With

increasing TS_{FS} SD addition has to increase to achieve energy self-sufficient operation as shown in Figure 2(b). Y_{SD} is generally lower than Y_{FS}, thus, Y_{CFS}' decreases with higher $X_{SD/FS,TS}$ (Ronsse *et al.* 2013; Liu *et al.* 2014; Ward *et al.* 2014). Figure 2(c) also shows that Y_{CFS}' decreases with increasing pyrolysis temperature, which is related to the fact that both Y_{SD} and Y_{FS} decrease with increasing pyrolysis temperature.

Figure 2(d) shows $HHV_{CFS,char}'$ with increasing TS_{FS} and at different pyrolysis temperatures under energy self-sufficient operation. At 300 °C the pyrolysis temperature $HHV_{CFS,char}'$ increases with increasing TS_{FS} while it decreases at pyrolysis temperatures ≥ 400 °C. $HHV_{CFS,char}'$ is similar at a TS_{FS} of circa 20% for all pyrolysis temperatures. This interesting finding can be explained by the fact that the HHV of SD-derived char ($HHV_{SD,char}$) increases with increasing pyrolysis temperature, while the HHV of FS-derived char ($HHV_{FS,char}$) decreases (Ward *et al.* 2014; Ronewicz *et al.* 2017). When TS_{FS} increases, less SD has to be added to achieve energy self-sufficient operation, thus, $HHV_{CFS,char}'$ approximates $HHV_{FS,char}$. In turn, when TS_{FS} decreases, more SD has to be added and $HHV_{CFS,char}'$ approximates $HHV_{SD,char}$. This finding also indicates that if a high $HHV_{CFS,char}'$ is desired and FS with $TS_{FS} < 20\%$ is used, i.e. a significant amount of sawdust has to be added (circa $X_{SD/FS,TS} > 1$), a high pyrolysis temperature should be favored, while a low pyrolysis temperature should be favored at $TS_{FS} > 20\%$.

Discussion of the results in context of on-site sanitation in developing countries

Other than in industrialized countries, where composting toilets are common for on-site sanitation, in developing countries predominantly pit latrines and septic tanks are used (Strande *et al.* 2014, 2018). As shown in Table 1, FS from these sources exhibits low TS (<10%). When applying the proposed approach of adding SD to FS prior to pyrolysis, several considerations have to be made. As indicated by our results a relatively high amount of SD has to be added to achieve energy self-sufficient operation, because of the low TS. Thus, the approach is limited by the availability of SD. Optionally, instead of SD, other organic bulking materials such as rice husk or corn husk may be used to increase TS (Libra *et al.* 2011; Ronsse *et al.* 2013). However, their applicability needs to be elucidated as these materials may behave differently during pyrolysis. The amount of required SD may also be reduced by an

additional mechanical dewatering step prior to SD addition that increases TS. For the approach discussed here, we generally recommend favoring low pyrolysis temperatures (300 °C) when aiming for high yield, e.g. when char should be produced for soil amendment. Conversely, when aiming for char with high HHV, e.g. for fuel production, a high pyrolysis temperature should be applied (600 °C). The latter aspect is contrary to pyrolysis of pure FS that exhibits an opposite trend, i.e. an increased HHV is obtained at lower pyrolysis temperatures (Ward *et al.* 2014; Ronewicz *et al.* 2017).

SUMMARY AND CONCLUSIONS

CFS exhibits favorable feedstock characteristics for pyrolysis, although a broader fundament of data, including fecal sludge from different sources, e.g. people with different diets, as well as different bulking materials is needed for further validation. The addition of SD to FS enables energy self-sufficient pyrolysis operation, even when using FS with low TS ($\geq$5%). It also allows the production of pyrolysis char with high HHV and low ash content. HTC of CFS is also suitable, however, due to its high TS a dilution of the feedstock is required to enable proper reactor mixing. In summary, carbonization provides a promising concept for the time-efficient, decentralized and hygienically safe valorization of CFS that can be applied as an alternative to conventional treatment approaches.

ACKNOWLEDGEMENTS

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at http://dx.doi.org/10.2166/washdev.2019.047.

REFERENCES

Afolabi, O. & Sohail, M. 2017 Comparative evaluation of conventional and microwave hydrothermal carbonization of human biowaste for value recovery. *Water Sci. Technol.* **75** (12), 2852–2863.

Afolabi, O., Sohail, M. & Thomas, C. 2015 Microwave hydrothermal carbonization of human biowastes. *Waste Biomass Valorization* **6** (2), 147–157.

Anand, C. K. & Apul, D. S. 2014 Composting toilets as a sustainable alternative to urban sanitation – a review. *Waste Manage.* **34** (2), 329–343.

Arlabosse, P., Ferrasse, J.-H., Lecomte, D., Crine, M., Dumont, Y. & Léonard, A. 2011 Efficient sludge thermal processing: from drying to thermal valorization. In: *Modern Drying Technology* (E. Tsotsas & A. S. Mujumdar eds). Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany.

ATV-Merkblatt 270 1997 *Entsorgung von Inhalten mobiler Toiletten mit Sanitärzusätzen (Disposal of Contents Derived From Mobile Toilets Using Sanitary Additives)* (Code of practice). German Association for Water, Wastewater and Waste (DWA), Munich, Germany.

Bagreev, A., Bandosz, T. J. & Locke, D. C. 2001 Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer. *Carbon* **39** (13), 1971–1979.

Bridle, T. R. & Pritchard, D. 2004 Energy and nutrient recovery from sewage sludge via pyrolysis. *Water Sci. Technol.* **50** (9), 169–175.

Danso-Boateng, E., Holdich, R. G., Shama, G., Wheatley, A. D., Sohail, M. & Martin, S. J. 2013 Kinetics of faecal biomass hydrothermal carbonisation for hydrochar production. *Appl. Energy* **111** (Supplement C), 351–357.

Danso-Boateng, E., Holdich, R. G., Martin, S. J., Shama, G. & Wheatley, A. D. 2015 Process energetics for the hydrothermal carbonisation of human faecal wastes. *Energ. Convers. Manage.* **105**, 1115–1124.

Diener, S., Semiyaga, S., Niwagaba, C. B., Muspratt, A. M., Gning, J. B., Mbéguéré, M., Ennin, J. E., Zurbrugg, C. & Strande, L. 2014 A value proposition: resource recovery from faecal sludge – can it be the driver for improved sanitation? *Resour. Conserv. Recycl.* **88**, 32–38.

DSTATIS 2015 *Öffentliche Wasserversorgung und öffentliche Abwasserentsorgung – Strukturdaten zur Wasserwirtschaft (Public Water Supply and Wastewater Disposal – Data on Water Management)* (No. Fachserie 19 Reihe 2.1.3). Federal Statistical Office of Germany, Wiesbaden, Germany.

Feachem, R. G., Bradley, D. J., Garelick, H. & Mara, D. D. 1981 *Appropriate Technology for Water Supply and Sanitation: Health Aspects of Excreta and Sullage Management: A State-of-the-art Review* (No. 11508). The World Bank, Washington, DC, pp. 1–318.

Gerber, H. 2011 Pflanzenkohleherstellung im PYREG Verfahren (Biochar production with PYREG process). In: *Conference Proceedings of 72nd Symposium of ANS e.V*, Berlin, Germany.

Germer, J., Boh, M. Y., Schoeffler, M. & Amoah, P. 2010 Temperature and deactivation of microbial faecal indicators during small scale co-composting of faecal matter. *Waste Manage. (NY)* **30** (2), 185–191.

Gold, M., Cunningham, M., Bleuler, M., Arnheiter, R., Schönborn, A., Niwagaba, C. & Strande, L. 2018 Operating parameters for three resource recovery options from slow-pyrolysis of faecal sludge. *J. Water Sanit. Hyg. Dev.* **8** (4), 707–717.

Heinss, U., Larmie, S. A. & Strauss, M. 1998 *Solids Separation and Pond Systems For the Treatment of Faecal Sludges in the Tropics*. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Huang, H., Yang, T., Lai, F. & Wu, G. 2017 Co-pyrolysis of sewage sludge and sawdust/rice straw for the production of biochar. *J. Analyt. Appl. Pyrolysis* **125**, 61–68.

Inguanzo, M., Domínguez, A., Menéndez, J. A., Blanco, C. G. & Pis, J. J. 2002 On the pyrolysis of sewage sludge: the influence of pyrolysis conditions on solid, liquid and gas fractions. *J. Analyt. Appl. Pyrolysis* **63** (1), 209–222.

Larsen, T. A., Udert, K. M. & Lienert, J. 2013 *Source Separation and Decentralization for Wastewater Management*. IWA Publishing, London.

Li, J., Plougonven, E., Fraikin, L., Salmon, T., Toye, D., Nistajakis, E. & Léonard, A. 2016 Positive operations on wastewater sludge drying: comparison of back-mixing and sawdust addition. *Energy Fuels* **30** (4), 3014–3019.

Libra, J. A., Ro, K. S., Kammann, C., Funke, A., Berge, N. D., Neubauer, Y., Titirici, M.-M., Führner, C., Bens, O., Kern, J. & Emmerich, K.-H. 2011 Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* **2** (1), 71–106.

Liu, X., Li, Z., Zhang, Y., Feng, R. & Mahmood, I. B. 2014 Characterization of human manure-derived biochar and energy-balance analysis of slow pyrolysis process. *Waste Manage.* **34** (9), 1619–1626.

Lopez Zavala, M. A. & Funamizu, N. 2006 Design and operation of the bio-toilet system. *Water Sci. Technol.* **53** (9), 55–61.

McGaughy, K. & Reza, M. T. 2017 Hydrothermal carbonization of septic tank waste: fate of macronutrients, micronutrients, and heavy metals. In: *Presentation Presented at the AIChE 2017 Annual Meeting*, Ohio, USA.

Niwagaba, C., Kulabako, R. N., Mugala, P. & Jönsson, H. 2009 Comparing microbial die-off in separately collected faeces with ash and sawdust additives. *Waste Manage.* **29** (7), 2214–2219.

Owens, E. & Cooley, S. 2013 *Calorific Value of Irish Woodfuels*. Coford – Department of Agriculture, Food and the Marine, Dublin, Ireland.

Ronewicz, K., Kluska, J., Heda, Ł. & Kardaś, D. 2017 Chemical and physical properties of pine wood during pyrolysis. *Drvna Industrija: Sci. J. Wood Technol.* **68** (1), 29–36.

Ronsse, F., van Hecke, S., Dickinson, D. & Prins, W. 2013 Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy* **5** (2), 104–115.

Rose, C., Parker, A., Jefferson, B. & Cartmell, E. 2015 The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Crit. Rev. Environ. Sci. Technol.* **45** (17), 1827–1879.

Semiyaga, S., Okure, M. A. E., Niwagaba, C. B., Nyenje, P. M. & Kansiime, F. 2017 Dewaterability of faecal sludge and its implications on faecal sludge management in urban slums. *Int. J. Environ. Sci. Technol.* **14** (1), 151–164.

Sossou, S., Sou/Dakouré, M., Hijikata, N., Quenum, A., Maiga, A. H. & Funamizu, N. 2014 Removal and deactivation of intestinal parasites in aerobic mesophilic composting reactor for urine diverting composting toilet. *Compost Sci. Util.* **22** (4), 242–252.

Strande, L., Ronteltap, M. & Brdjanovic, D. 2014 *Faecal Sludge Management: Systems Approach for Implementation and Operation*. IWA Publishing, London.

Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B. J. & Niwagaba, C. B. 2018 Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. *J. Environ. Manage.* **223**, 898–907.

Strauss, M., Larmie, S. A., Heinss, U. & Montangero, A. 2000 Treating faecal sludges in ponds. *Water Sci. Technol.* **42** (10–11), 283–290.

Troy, S. M., Nolan, T., Kwapinski, W., Leahy, J. J., Healy, M. G. & Lawlor, P. G. 2012 Effect of sawdust addition on composting of separated raw and anaerobically digested pig manure. *J. Environ. Manage.* **111**, 70–77.

Vreugdenhil, B. J. & Zwart, R. W. R. 2009 *Tar Formation in Pyrolysis and Gasification*. Energy Research Centre of the Netherlands, Sint Maartensvlotbrug, The Netherlands.

Wang, Z., Chen, D., Song, X. & Zhao, L. 2012 Study on the combined sewage sludge pyrolysis and gasification process: mass and energy balance. *Environ. Technol.* **33** (22–24), 2481–2488.

Ward, B. J., Yacob, T. W. & Montoya, L. D. 2014 Evaluation of solid fuel char briquettes from human waste. *Environ. Sci. Technol.* **48** (16), 9852–9858.

Yan, Q., Toghiani, H., Yu, F., Cai, Z. & Zhang, J. 2011 Effects of pyrolysis conditions on yield of bio-chars from pine chips. *Forest Products J.* **61** (5), 367–371.

Zhang, X., Zhang, L. & Li, A. 2017 Hydrothermal co-carbonization of sewage sludge and pinewood sawdust for nutrient-rich hydrochar production: synergistic effects and products characterization. *J. Environ. Manage.* **201**, 52–62.

Zhu, J., Wan, L., Chen, H., Zhu, Y. & Yang, L. 2017 Pilot test of co-pyrolysis characteristics of wet sewage sludge and sawdust in an external heating moving bed. *Energy Procedia.* **105**, 570–575.