

Review Paper

To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge

Nienke Andriessen, Barbara J. Ward and Linda Strande

ABSTRACT

Resource recovery from faecal sludge can take many forms, including as a fuel, soil amendment, building material, protein, animal fodder, and water for irrigation. Resource recovery as a solid fuel has been found to have high market potential in Sub-Saharan Africa. Laboratory- and pilot-scale research on faecal sludge solid fuel production exists, but it is unclear which technology option is most suitable in which conditions. This review offers an overview and critical analysis of the current state of technologies that can produce a dried or carbonized solid fuel, including drying, pelletizing, hydrothermal carbonization, and slow-pyrolysis. Carbonization alters fuel properties, and in faecal sludge, it concentrates the ash content and decreases the calorific value. Overall, a non-carbonized faecal sludge fuel is recommended, unless a carbonized product is specifically required by the combustion technology or end user. Carbonized and non-carbonized fuels have distinct characteristics, and deciding whether to char or not to char is a key judgement in determining the optimal solid fuel technology option. Based on the existing evidence, this review provides a decision-making structure for selecting the optimal technology to produce a faecal sludge solid fuel and identifies the top research needs prior to full-scale implementation.

Key words | carbonization, energy recovery, faecal sludge, fecal sludge, onsite sanitation, pyrolysis

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INTRODUCTION

Faecal sludge accumulates in onsite sanitation technologies and is not transported through a sewer. It is the liquid, slurry or semi-solid matter that results from the combination of excreta, flush water, anal cleansing material, and other substances that are stored inside onsite sanitation technologies such as septic tanks and pit latrines (Strande *et al.* 2014). Onsite sanitation is an appropriate solution to fulfil sanitation needs, with appropriate management of the entire service chain. Currently, 1.8 billion people globally rely on

faecal sludge management for their sanitation needs (Berendes *et al.* 2017). The majority of faecal sludge is not safely managed or adequately treated, and ends up in the immediate urban environment, posing a severe risk to human and environmental health (Peal *et al.* 2014).

Valorization of end products from faecal sludge can serve as an incentive for appropriate faecal sludge management (Diener *et al.* 2014). Revenues from resource recovery could partially offset operation costs, incentivize proper operation and maintenance, and stimulate regular emptying and delivery of faecal sludge to treatment plants. There are various forms of treatment end products for the recovery of resources from faecal sludge. Soil conditioners, compost, and effluent for irrigation are well-established end products

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(Diener *et al.* 2014). Other possibilities that are starting to be implemented include the production of animal feed (from black soldier fly larvae or fodder crops), incorporation in building materials, and energy in the form of fuel, electricity or heat, but limited information is available for implementation. The type and form of resource recovery should always meet local conditions and user acceptance, and whenever possible, should be decided early in the planning process, so that appropriate treatment objectives can be set to ensure public health (Reymond 2014). A market-driven assessment can help to inform which end product is most marketable in the specific location (Andriessen *et al.* 2017). Research indicates that there is a high demand for solid fuels in urban areas of Sub-Saharan Africa, especially from manufacturing industries (e.g. brick and cement industries) (Diener *et al.* 2014).

Wood and waste biomass (e.g. coffee husk, rice husk, and sawdust) are conventionally used as a solid fuel in many industries in low- and middle-income countries. Solid fuel products can be either in carbonized or non-carbonized forms. Carbonization is often used to convert dried biomass (e.g. wood) into a fuel that more closely resembles coal, and can improve the energy density (calorific value) of the fuel. Wastewater sludge is also used as a fuel in co-combustion with coal or other solid fuels in industrial setups, both in carbonized and dried form (Werther & Ogada 1999; Fytli & Zabaniotou 2008). Alternatively, it is incinerated, with or without energy recovery (Werther & Ogada 1999). As faecal sludge management has only been acknowledged as a sustainable solution within the last 30 years (USEPA 1984), resource recovery and treatment research lag behind research on centralized wastewater treatment. Full-scale implementations are quite limited; however, there is a growing body of work on faecal sludge fuels, based on laboratory- and pilot-scale research. Possible solid fuel products include dried fuels and char fuels in powder, pellet, or briquette form.

This review presents relevant laboratory- and pilot-scale studies on the production of solid fuels from faecal sludge in order to evaluate what is working, to make recommendations for practitioners, and to identify areas for future research. The article first defines the range of possible input faecal sludge characteristics and output end products and discusses what factors influence the selection of fuel

type, and technical aspects of technologies to produce faecal sludge solid fuels. Afterwards, a critical comparison of technologies and guidelines to select appropriate technology and solid fuel end product is presented based on their required inputs, technical complexity, energy requirement, land area, and environmental impact.

TECHNOLOGY INPUTS AND OUTPUTS

This review covers faecal sludge that has been dewatered to at least 20% dry solids (ds) and to solid fuel end products that are at least 90% ds. Twenty percent ds was selected as the starting point, because although faecal sludge is typically <6% ds when it is emptied from onsite containments, technologies such as drying beds that dewater to 20% ds are relatively standard (Strande *et al.* 2014). Following dewatering to 20% ds, further removal of moisture requires drying, removing bound water in the faecal sludge via evaporation. As illustrated in Figure 1, the technologies that can produce solid fuels require varying levels of dewatered or dried faecal sludge as input material. In this review, unplanted drying beds, which passively dry faecal sludge to $\geq 90\%$ ds to produce a dried fuel for direct combustion, are considered as the 'baseline' option, to which other technology options are compared. To produce pellets, conventional pelletizers that use binders require approximately 70% ds (Nikiema *et al.* 2013), the Bioburn pelletizer 30–60% ds (Turyasiima *et al.* 2016), and the LaDePa process 20–30% ds (Harrison & Wilson 2012; Septien *et al.* 2018). For carbonized options, pyrolysis requires sludge dried to 70–90% ds as wetter sludge requires increased energy consumption (Bond *et al.* 2018), whereas hydrothermal carbonization (HTC) functions optimally with dewatered faecal sludge at 20% ds (Fakkaew *et al.* 2015b). Dewatering and the required level of input dryness are important considerations when selecting technologies to produce fuel, as dewatering and drying require varying levels of time and space depending on the technologies used.

The breakeven point for positive energy recovery from faecal sludge combustion is as low as 27% ds (Murray Muspratt *et al.* 2014), though, in reality, end users prefer dried fuel. Ninety percent ds is conventionally considered an appropriate dryness for solid fuel to meet industrial customer demands (Gold *et al.* 2014; Seck *et al.* 2015).

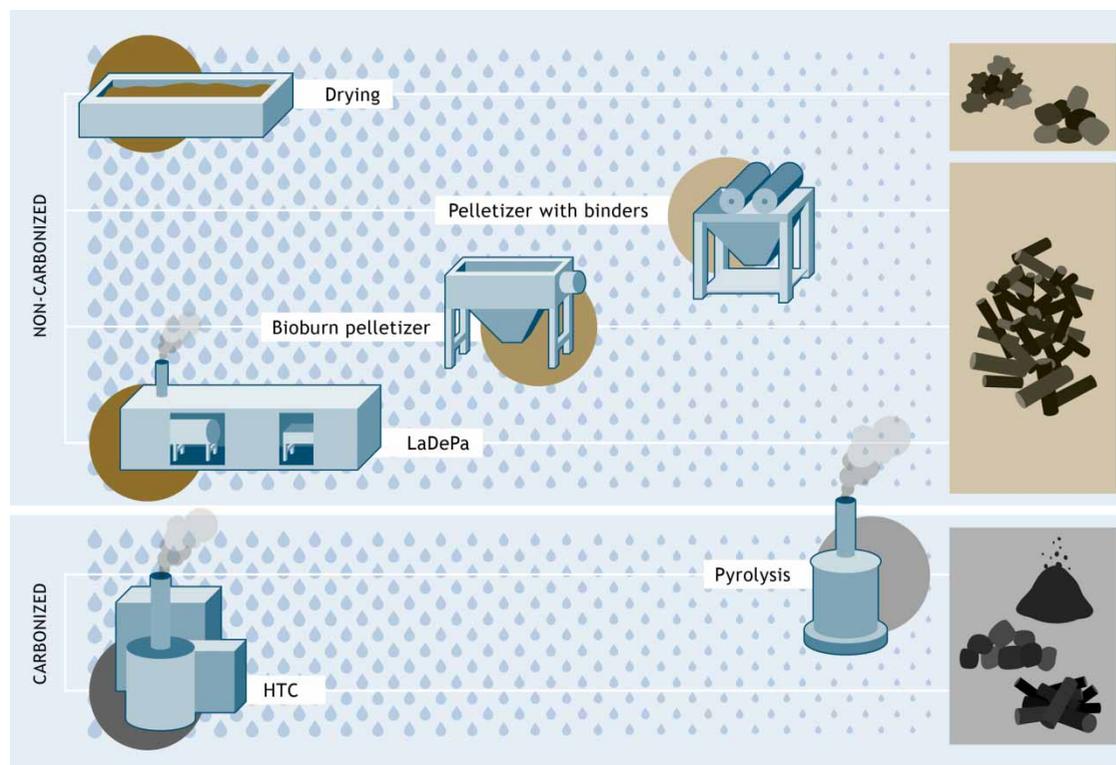


Figure 1 | An overview of technological options for producing solid fuel, starting from dewatered faecal sludge at 20% ds and ending at non-carbonized or carbonized solid fuel end products. The position of the technology icons from left to right indicates the required dryness of the input sludge for each technology, as indicated by the size of the droplets, ranging from 20% ds on the left to 90% ds on the right.

CONSIDERATIONS FOR EVALUATING FAECAL SLUDGE FUELS

A market assessment should always be conducted as a first step to determine the most appropriate resource recovery product in the local context. If it becomes evident that potential customers have an insurmountable aversion towards using faecal sludge as fuel, another type of resource recovery product should be considered. Once a market demand study has identified that solid fuels are the desired end product, it is important to determine which type of solid fuel will best meet demand and specific needs of consumers. Specifically, fuel quality and form should be compatible with the desired end use.

Solid fuels are composed of ds and moisture. The ds consist of combustible material and incombustible ash. The energy density contained within the fuel is reported as calorific value, the heat produced during complete combustion of a specific mass of dry fuel. Only the combustible

material contributes positively to the energy density of fuel; generally, the higher the ash fraction in fuel, the lower its calorific value. Standard metrics for solid fuel quality assessment fractionate combustible material into volatile matter and fixed carbon (proximate analysis), or into C, O, H, N, and S (ultimate analysis) (Jenkins *et al.* 1998). Volatile matter and fixed carbon both contain energy; however, empirical studies of biomass fuels have shown that fixed carbon has a higher positive impact on a calorific value than volatile matter (Yin 2011). The elemental fractionation of fuel can also influence calorific value (Sheng & Azevedo 2005; Yin 2011) and provide information about levels of SO_x and NO_x emissions produced during combustion (Demirbaş 2003).

The qualities of faecal sludge-derived solid fuel end products are affected by the characteristics of the input sludge. Faecal sludge characteristics are highly variable, depending on residence time in containment, differences in sanitation technologies and practices, and numerous other factors

(Strande *et al.* 2014). Several studies have reported that anaerobic digestion decreases the calorific value of recovered solids by reducing the readily degradable organic fraction (Gold *et al.* 2014; Bond *et al.* 2018). For example, Zuma *et al.* (2015) measured calorific value throughout a ventilated improved pit (VIP) latrine. Calorific value decreased with depth, which was attributed to deeper layers having a longer residence time over which to degrade. Decreased calorific value tracked with increased ash fraction in deeper layers of the pit. Although recalcitrant organic matter remains after stabilization and contributes to calorific value (Cao & Pawłowski 2012; Murray Muspratt *et al.* 2014), the inorganic ash fraction increases as a result of anaerobic digestion of available organic material, releasing carbon as methane and carbon dioxide and negatively affecting the energy density of the end product (Murray Muspratt *et al.* 2014).

Sand contributes significantly to the ash fraction in faecal sludge fuels. Infiltration of sand and soil during storage, ablution, collection, and dewatering on drying beds decreases faecal sludge fuel quality by increasing the ash fraction (Seck *et al.* 2015). Hafford *et al.* (2019) observed that 5% of the ash fraction in faeces consisted of sand, compared to 9–39% of the ash fraction in thermally dried faecal sludge (not dried on drying beds). Sand drying beds can contribute between 6% (Seck *et al.* 2015) and 20% (Ward *et al.* 2017) of additional ash. In Tanzania, the ash fraction in faecal sludge char produced from sludge dewatered and dried on unplanted drying beds comprised 77% sand on average (Mwamlima *et al.* 2017).

The differences in sand and ash content between faeces, faecal sludge and faecal sludge char show that the variability is extremely high, but could potentially partially be controlled with sand reducing measures. Possibilities to keep sand from contaminating faecal sludge fuel include a geotextile layer on the surface of sand drying beds, or dewatering and drying with geotubes (Mwamlima *et al.* 2017; Ward *et al.* 2017). For example, char from faecal sludge that was dried using geotubes had 14% less sand than char from faecal sludge that was dried on sand drying beds (Mwamlima *et al.* 2017).

The requirements of end users of faecal sludge fuels determine the form and quality of the end product. Diener *et al.* (2014) reported that industrial end users in Kampala

were willing to use faecal sludge as a fuel, if its form was compatible with their existing combustion technologies. For example, kilns typically require fuel in powdered form (Diener *et al.* 2014; Gold *et al.* 2017), while most gasifiers and many boilers require densified fuel pellets or briquettes (Saidur *et al.* 2011; Ward *et al.* 2017). When fuels need to be transported offsite of the treatment plant, pellets work much better than powder (easier to load and keep from blowing away during transport) (Stelte *et al.* 2011). Fuel quality also needs to be taken into account: in addition to reducing calorific value, high-ash fractions can pose technical challenges for combustion and gasification technologies due to the formation of metal oxide deposits (Saidur *et al.* 2011; Ward *et al.* 2017). Simpler combustion setups like brick-making kilns do not appear to suffer from ash deposition issues during pilots conducted with high-ash faecal sludge fuels (Gold *et al.* 2017).

With the current state of faecal sludge solid fuel production, industrial end users are identified as the main target market (Diener *et al.* 2014). Industrial end users have a less complicated supply chain, more robust combustion technologies, and a constant demand for high volumes of fuel compared to non-industrial or domestic end users (e.g. households and schools) (Diener *et al.* 2014). In addition, industrial end users are better suited to handle hazards arising from the use of (not completely pathogen-free) faecal sludge fuels. Industrial end users are also likely better equipped to control emissions and maintain air quality standards (Werther & Ogada 1999). Social acceptance of using a faecal sludge product may also be easier to obtain for industrial use (Diener *et al.* 2014).

However, even when resource recovery efforts are concentrated at centralized treatment facilities, faecal sludge fuel production volume alone may not be able to fulfil the demand of large industrial customers (Ward *et al.* 2017). For example, fuel demand from cement manufacturers in Dakar and Kampala is 4–40 times higher than the volume of treated faecal sludge in these cities (Gold *et al.* 2017). Potentially, large-scale demand could also help stimulate the entire faecal sludge management service chain. Co-management with other organic waste streams can increase the volume and quality of faecal sludge fuels produced (Ward *et al.* 2017; Hafford *et al.* 2019). However, candidate waste streams for co-processing must be critically evaluated, as

frequently they are already used. Proper co-management should not dilute high-value fuels with faecal sludge, but instead combine low-value or valueless waste streams to create a more useable end product, for example, by briquetting previously unused and difficult to transport powdered wastes with dewatered faecal sludge (Palmer *et al.* 2017). The suitability of co-management will depend on the availability and properties of organic waste streams.

TECHNOLOGY OPTIONS

Once the qualities of the input faecal sludge (calorific value, ash, and available volumes) and intended end use (a type of end user and consequent requirements for form and output dryness) have been identified, available technologies that meet these requirements can be assessed. In this section, technologies are divided into those producing non-carbonized and carbonized fuels. For each group of technologies, typical end product fuel qualities are presented, followed by a detailed overview of each technology.

Non-carbonized fuel

Dried faecal sludge is directly combustible. Summarized in Table 1 are fuel characteristics of dried faecal sludge and faeces reported in the literature. Murray Muspratt *et al.* (2014) were the first to report the calorific value of faecal sludge for use as a solid fuel. They observed the calorific value of faecal sludge to be fairly consistent across cities; however, subsequent studies have observed more variations (Table 1). In general, the calorific value of faecal sludge is comparable to that of anaerobically digested wastewater sludge, which could be explained by partial digestion during storage in containment. The ash content is higher in faecal sludge than in wastewater sludge, which is likely due to the introduction of sand and soil during storage, collection, and treatment. The values reported in Table 1 show a lower calorific value for dried faecal sludge than for dried faeces. This is likely due to factors affecting the material during storage in the containment, such as the breakdown of energy-dense bonds in readily degradable organic material over time, and mixing with inert materials. Dried faecal sludge also has much higher variability than dried

faeces in both calorific value and ash content, which could be explained by the aforementioned reasons, and the varying conditions in containments.

Dried faecal sludge performed comparably to common biomass fuels in pilot-scale industrial kiln trials (Gold *et al.* 2017), although high-ash content may present problems for more complex combustion or gasification setups unless they are specifically designed to handle high-ash fuels (Ward *et al.* 2017). Upper limits for fuel ash fraction in cement kilns and power plant boilers have been reported as 15% and 20% dw, respectively (Velis *et al.* 2012). Gold *et al.* (2017) reported a higher range of <60–15% ash as limits for industrial kilns. In addition to ash fraction, the combustion temperature, combustion atmosphere, and fractions of alkali ash and chlorine are important factors in determining how much sludge to add during co-combustion (Wzorek 2012; WBCSD 2014). No foul odours have been observed while burning dried sludge in industrial kilns (Nantambi *et al.* 2016).

Drying technologies

Drying of faecal sludge to $\geq 90\%$ ds can be achieved either passively or actively. Passive drying relies on natural mechanisms of evaporation (e.g. wind and sun) and does not entail the addition of energy, for example, on drying beds or other surfaces. This form of drying can take several weeks to months, depending on the faecal sludge, treatment design, loading rates, and climate (Cofie *et al.* 2006). For example, in Tanzania, drying time to dry to $\geq 90\%$ ds on unplanted drying beds varied between 21 and 83 days, for loading rates between 100 and 200 kg/m²/year (Moto *et al.* 2018). Required land area for unplanted drying beds is significant and is an important consideration for their use in dense urban areas. For example, at the Cambérène treatment plant in Dakar, Senegal (designed for 100 m³/day), drying beds take up 1,300 m² of land area (Strande *et al.* 2014).

Active drying entails supplying external energy as heat or hot air (thermal drying) (Lowe 1995) or microwaves (Mawioo *et al.* 2016), mechanical or manual turning of the sludge to enhance evaporation (Seck *et al.* 2015; Ward *et al.* 2017), or mechanical ventilation (Bux *et al.* 2002). Active drying is used to accelerate the drying process compared to passive drying, and can increase processing capacity at treatment plants and/or reduce required land

Table 1 | Studies that report calorific value (as higher heating value) per dry weight of end product and ash content of faecal sludge, faeces, and representative ranges of wastewater sludge (all based on dry weight)

Reference	Calorific value (MJ/kg)	Ash content (% dw)	Location
<i>Faecal sludge</i>			
Murray Muspratt <i>et al.</i> (2014)	19.1 ($n = 30$)	NA	Kumasi, Ghana
	16.6 ($n = 48$)	NA	Dakar, Senegal
	16.2 ($n = 102$)	NA	Kampala, Uganda
Liu <i>et al.</i> (2014)	18.1 ($n = \text{NA}$)	17.1	Beijing, China
Zuma (2015)	13.1 ($n = 84$)	NA	Durban, South Africa
Seck <i>et al.</i> (2015)	12.2 ($n = 5$)	41.7	Dakar, Senegal
Koottatep <i>et al.</i> (2016)	16.9 ^a ($n = \text{NA}$)	31.9 ^a	Pathumthani, Thailand
Gold <i>et al.</i> (2017)	10.9 ($n = \text{NA}$)	58.5	Kampala, Uganda
	13.4 ($n = 4$)	47.0	Dakar, Senegal
Mwamlima <i>et al.</i> (2017)	8.3 ($n = 3$)	51.3	Dar es Salaam, Tanzania
Pivot Works Ltd (2017)	16.9 ($n = 33$)	15.7	Kigali, Rwanda
Nyaanga <i>et al.</i> (2018)	13.1 ($n = 5$)	48.3	Nakuru, Kenya
Hafford <i>et al.</i> (2019)	12.5 ($n = 6$)	44.0	Boulder, USA
	14.3 ($n = 3$)	34.0	Kampala, Uganda
<i>Faeces</i>			
Rose <i>et al.</i> (2015)	17.2 ^b	7.5–16	NA
Onabanjo <i>et al.</i> (2016)	24.7	14.6	Cranfield, UK
Somorin <i>et al.</i> (2017)	23.4	18.3	Cranfield, UK
Afolabi <i>et al.</i> (2017)	19.5	13.3	Loughborough, UK
<i>Wastewater sludge ranges</i>			
Primary sludge (Fytili & Zabaniotou 2008; Kim & Parker 2008)	23–29	NA	NA
Activated sludge (ECN; Fytili & Zabaniotou 2008; Kim & Parker 2008)	16–23	18.2–23	NA
Anaerobically digested sludge (ECN; Fytili & Zabaniotou 2008; Kim & Parker 2008)	9–13	14–26	NA

The number of samples (n) is in parentheses. NA means that the information was not available.

^aRecalculated to dry weight.

^bRecalculated based on kcal/kg, design guidelines.

area. For example, Bux *et al.* (2002) found that solar drying with active ventilation by fans could reduce land area by 25% compared to passive drying beds. Manual turning of sludge on drying beds can reduce drying time by 20–30% (Seck *et al.* 2015; Ward *et al.* 2017).

Pelletizing technologies

Pelletization is the process of compressing biomass into pellets. Conventional pelletizing machines can be used for

faecal sludge fuels and also in animal feed and compost pellet production. These compress the material to form a pellet and require binders to stick the biomass together. Potential binders that have been reported to work with dried faecal sludge are cassava starch, beeswax, clay, ligno-sulfonates, and molasses (Nikiema *et al.* 2014a). Binders can affect the calorific value of pellets depending on the calorific value of the chosen binder and the amount used. Optimum dryness required for conventional pelletizing is dependent on the type of binder and the type of sludge,

and has been reported around 70% ds (Nikiema *et al.* 2013). Further drying of the pellets is then needed to reach $\geq 90\%$ ds, depending on the requirements of the combustion technology and end user. One reported conventional pelletizer is 1.2 m length, 0.5 m width and 1.4 m height, and can process faecal sludge at 60–100 kg/hour (Nikiema *et al.* 2013).

Another type of pelletizer is the Bioburn pelletizer (www.bioburn.ch). The Bioburn extruder twists the pellets in a helical fashion during extrusion, which produces stronger pellets than conventional pelletizers (Nikiema *et al.* 2014b). The pelletizer can process sludge with 30–60% ds compared to the 70% ds required for conventional pelletizers. This difference in moisture allows for pellets to be formed without the use of a binder. After processing, faecal sludge pellets produced with the Bioburn system dried passively to 90% ds in 1 week, compared to several weeks or months on conventional drying beds (Gold *et al.* 2016; Ward *et al.* 2017). Even if not used for fuel, the Bioburn pelletizing process can increase the drying capacity of a treatment plant. One Bioburn pelletizer unit has a footprint of approximately 1–2 m² and can process faecal sludge at a rate of 20–35 kg/hour/pelletizing unit (wet weight) (Nikiema *et al.* 2014b; Bioburn AG 2016). As the system is modular, additional pelletizing units can be installed to meet processing demand.

The LaDePa (Latrine Dehydration and Pasteurization) pelletizer technology produces sanitized pellets from faecal

sludge with 20–35% ds, also without a binder. Sludge is extruded through a grid onto a porous conveyer belt while partially drying with heated air and then treated with infrared radiation to a temperature of 180–220 °C for 8 minutes to kill all pathogens (Septien *et al.* 2018). The end product is a pellet of approximately 60–80% ds. The LaDePa machine was developed in response to local challenges in Durban, South Africa, where thick sludge from VIP latrines with solid waste needed to be treated. One unit is the size of a shipping container and can process a maximum of 20 tonne/hour (Nikiema *et al.* 2013).

Carbonized fuel

Carbonization increases the fraction of fixed carbon and reduces the fraction of volatile matter, including impurities such as chlorine and sulfur (Zethraeus 2012; Parshetti *et al.* 2013). Reducing volatile matter by carbonizing can also reduce odours (Shinogi & Kanri 2003), and the high temperatures maintained during carbonization can sanitize the end product, which might be desired depending on the intended use of the fuel. Characteristics of carbonized fuel made from faecal sludge and faeces reported in the literature are summarized in Table 2. Char can be produced through two distinct processes, pyrolysis and HTC, which produce fuels with different characteristics. These processes are

Table 2 | Published proximate analysis results of char from slow-pyrolysis of faecal sludge and faeces, and hydrochar from HTC of faecal sludge and faeces

Source	Calorific value (MJ/kg)	Ash content (% dw)	Volatile matter (% dw)	Fixed carbon (% dw)
<i>Faecal sludge char</i>				
Liu <i>et al.</i> (2014)	NA	26.3–62.5	6.3–60.5	13.2–31.2
Mwamlima <i>et al.</i> (2017)	4.7–8.9	63.5–78.6	11.4–17.9	9.5–18.5
Gold <i>et al.</i> (2018)	8.8–12.4	54.5–73.8	6.7–26.1	18.8–23.3
Hafford <i>et al.</i> (2019)	8.6–14.5	55.0–67.9	21.9–30.9	10.2–14.1
<i>Faecal sludge hydrochar</i>				
Koottatep <i>et al.</i> (2016)	16.1–28.5	33.2–41.4	39.8–44.8	12.6–24.6
Afolabi <i>et al.</i> (2017) ^a	19.3–25.2	21.1–23.6	76.4–78.9	NA
<i>Faeces char</i>				
Ward <i>et al.</i> (2014)	13.83–25.57	20.0–50.0	NA	NA
<i>Faeces hydrochar</i>				
Afolabi <i>et al.</i> (2017)	24.9–25.6	20.8–24.5	75.5–79.2	NA

NA means that the data were not available. The ranges summarize results from varying operating conditions (e.g. temperature and hold time).

^aAuthors refer to substance as a 'human faecal sludge', which includes fresh faeces, urine, toilet paper, and flush water. The reported characteristics resemble that of fresh faeces.

explained in the next sections. Considerably lower calorific values are reported for faecal sludge char made through pyrolysis (4.7–14.5 MJ/kg) than for hydrochar made through HTC (16.1–28.5 MJ/kg). This could be partially due to generally higher ash fractions in faecal sludge char compared to hydrochar as a result of better retention of volatile matter in hydrochar solids (volatile matter is often released as gas during pyrolysis). Carbonization technology does not appear to have as significant an effect on fuel quality when faeces is the feedstock. Faeces pyrolysed at 350 °C has comparable calorific value and ash content to faeces hydrochar.

When comparing [Tables 1 and 2](#), two studies show that pyrolysis does not appear to increase the calorific value of dried faecal sludge and increases the ash fraction in the fuel ([Mwamlima *et al.* 2017](#); [Hafford *et al.* 2019](#)). Conversely, HTC reportedly produces hydrochar with a higher calorific value than dried faecal sludge (from 16.3 MJ/kg dried faecal sludge to 18.8 MJ/kg hydrochar) ([Koottatep *et al.* 2016](#)). Adding a catalyst increases the reaction rate, but could affect calorific value positively or negatively. For faeces feedstocks, both low-temperature pyrolysis (at 350 °C) and HTC increase the calorific value compared to the dried fuel. Pyrolysis at higher temperatures decreases the calorific value of faecal sludge char ([Gold *et al.* 2018](#)), and pyrolysis results for faeces show that chars produced at 450 and 700 °C have lower calorific values than dried faeces ([Ward *et al.* 2014](#)). The values from [Mwamlima *et al.* \(2017\)](#) include char from anaerobically digested faecal sludge, which had a lower calorific value and volatile matter content, than char from faecal sludge that was not treated anaerobically.

Carbonizing technologies produce carbonized faecal sludge in the form of powder or chunks. Carbonized sludge can be directly combusted, or transformed into briquettes ([Mbuba *et al.* 2017](#)). Like conventional pellets, briquettes also need a binder and the same considerations apply as with using binders for producing pellets. Binders that have been used with faeces and faecal sludge char are molasses with lime, cassava starch, and clay ([Ward *et al.* 2014](#); [Lubwama & Yiga 2018](#); [Nyaanga *et al.* 2018](#)). Dewatered faeces has also been demonstrated as a binder for char dust from other biomass sources to make briquettes ([Palmer *et al.* 2017](#)).

Pyrolysis

Pyrolysis is the thermochemical treatment of biomass by heating to temperatures between 300 and 700 °C in the absence (or near absence) of oxygen. Slow-pyrolysis, which employs heating rates from 1 to 10 °C/min and residence times in the order of hours, is typically used when producing solid fuel, as it has higher char yields than pyrolysis processes with higher heating rates. In this article, the term pyrolysis refers to slow-pyrolysis. If the faecal sludge is not dry, the initial energy input will go toward volatilizing the water in the sludge before pyrolysis proceeds. A net positive energy balance could hypothetically be achieved with faecal sludge of >65% ds ([Liu *et al.* 2014](#); [Bond *et al.* 2018](#)). Pyrolysis can provide calorific value improvement for lignocellulosic biomass ([Demirbaş 2001](#)). With manure, faeces, and faecal sludge, this is not necessarily true ([Ward *et al.* 2014](#); [Mwamlima *et al.* 2017](#)). Operating conditions during pyrolysis can determine the composition of the faecal sludge char ([Cunningham *et al.* 2016](#)). For example, multiple articles note that a higher pyrolysis temperature increases the ash content of the end product ([Shinogi & Kanri 2003](#); [Cantrell *et al.* 2012](#); [Liu *et al.* 2014](#); [Ward *et al.* 2014](#)). The upper-range values for ash content of char in [Table 2](#) are all pyrolysed at higher (≥ 600) operating temperatures. Therefore, it is important to keep tight control over temperature during operation ([Gold *et al.* 2018](#)). A lower pyrolysis temperature (350 °C) is recommended when producing char for use as a fuel is the objective ([Gold *et al.* 2018](#)). End product yield (the distribution of how much of which end product (char, tar or gases) is produced) is also affected by operating conditions. For optimal char yield, a low heating rate (slow-pyrolysis) and low temperatures are recommended ([Lehmann & Joseph 2015](#); [Gold *et al.* 2018](#)), although gases and tar can also be used as fuel products. In general, pyrolysis of faecal sludge decreases its calorific value ([Mwamlima *et al.* 2017](#); [Hafford *et al.* 2019](#)). For faeces, pyrolysis could improve calorific value, but only at low pyrolysis temperatures (300 °C) ([Ward *et al.* 2014](#)). Pyrolysis has been applied at the bench- and pilot-scale with faecal sludge. Various pyrolysis reactors are available, which vary in technical complexity. A simple reactor could consist of two oil drums with a chimney and a gas burner, like the reactor used in Tanzania by [Mwamlima](#)

et al. (2017), or can be made from bricks as used by Atwijukye *et al.* (2018). These simple reactors can be built locally and are relatively small (<5 m²). To scale up, the number of units would be increased. More complex reactors include fixed bed and fluidized bed reactors that are also used for carbonization of other biomass. These systems need more technical skill for operation and maintenance, and commonly have a larger footprint than simple reactors (Lehmann & Joseph 2015).

HTC

HTC is the thermochemical conversion of wet biomass at temperatures ranging from 180 to 250 °C for 1–12 hours reaction time under pressure (>30 bar). A char yield of 50–80% is observed, and higher char yields are obtained at lower temperatures (Afolabi & Sohail 2017a). While there are multiple studies available on HTC of sewage sludge (Danso-Boateng *et al.* 2013; He *et al.* 2013; Parshetti *et al.* 2013), HTC of faecal sludge has only been reported by one group at the Asian Institute of Technology (Fakkaew *et al.* 2015a, 2015b; Koottatep *et al.* 2016). They found that HTC improved the calorific value of the faecal sludge fuel, from 16 to 19 MJ/kg (Koottatep *et al.* 2016). Faecal sludge input with 20% ds was found to be optimal for operation (Fakkaew *et al.* 2015b), which eliminates long drying times on drying beds. Liquid by-products need further treatment to remove organic matter before discharge into the environment. HTC reactors exist on a pilot scale, but few full-scale examples exist at this moment (Román *et al.* 2018). HTC of faecal sludge has been demonstrated in laboratory- and pilot-scale tests, and scaling up will require research on the behaviour of faecal sludge (e.g. ash content) in larger reactors. The heat distribution of larger-scale reactors is sensitive and will require more energy (Fakkaew *et al.* 2015a).

HTC has also been demonstrated at a laboratory scale with microwave technology. In this case, HTC temperatures are reached with microwaves instead of a conventional electric heating source (Afolabi & Sohail 2017a, 2017b). It is proposed that microwave technology could be an option for mobile processing of faecal sludge (Afolabi & Sohail 2017b).

CRITICAL COMPARISON

Comparison of technology options

Additional aspects of the technologies discussed above are compared in Table 3. Passive sludge drying does not use energy, but requires a large land surface, which is often not available in dense urban areas. If the land is scarce and the required energy investment is available, active drying is worth investigating. The theoretical amount of energy needed for complete thermal drying from 20% to 90% ds is 1,604 kWh/tonne of dried end product (calculated from Bond *et al.* (2018), calculations in Supplemental Information, available with the online version of this paper). That is very high compared to other active drying options, which makes it impractical to thermally dry up to 90% ds. Bux *et al.* (2002) show that low-temperature solar drying can be more economical than conventional thermal drying. Manual turning requires manpower, which may be more cost effective in some locations, and could reduce land area by 25% compared to passive drying beds (Gold *et al.* 2014). Where drying technologies are not available, technologies that can handle higher moisture content could be more appropriate than options requiring a high level of dryness. Realistically, a trade-off between maximizing dryness and minimizing processing time and surface area is often unavoidable.

A compacted end product (pellets or briquettes) is relevant in contexts where transportation is needed, or where the market demands fuel in these forms. Pelletizing requires relatively small energy input compared to the other processing technologies and can also facilitate faster drying. For example, the Bioburn pelletizer could reduce the land area for drying beds by 50% (Ward *et al.* 2017). Using binders can elevate costs, as some binders may be expensive or not locally available (Nikiema *et al.* 2014a). Co-processing with other biowastes can improve the physical strength of pellets (Turyasiima *et al.* 2016). The LaDePa process is an appropriate technology in places where thicker or dewatered sludge (20–35% ds) needs to be treated, or where a sanitized final product is required. With that input, the machine pelletizes and dries sludge in 8 minutes, which, compared to passive drying on drying beds, increases capacity immensely. However, the energy

Table 3 | Overview of characteristics of technologies that produce a solid fuel end product

Technology	Required input dryness (% ds)	Output dryness (% ds)	Energy input (kWh/tonne end product)	Pathogens in end product	Relative required land area for technology	CO ₂ equivalent (kg/MJ end product) ^a
Dried sludge (passive drying)	20 ^b	90	NA	+	•••	0.00603
Dried sludge (energy required)	20 ^b	90	79–101 (low-temperature solar drying) ^c 252–396 (conventional thermal drying) ^c	+	•/••	NA
Conventional pelletizers with binders	70	70	36–57 ^d	+	•	NA
Bioburn pelletizer	30–60	30–60	64 ^e	+	•	0.0088
LaDePa	20–30	80	507 ^f		••	NA
Pyrolysis	70–90	100	297 ^g		•	0.0502
HTC	20	100	392–533 ^g		•	NA

The listed energy inputs are for pre-drying (from 20% ds to technology input) and the technology operation, and do not include additional energy needed for post-drying after processing. Plus signs (+) indicate the presence of pathogens in the end product. Dots indicate the amount of land area required for a technology, with (•) indicating small area and (•••) indicating large area.

^aEgloff & Whett (2017).

^bFor the purpose of this paper, calculations started at 20, but for these options, the starting point could be the dryness of the raw faecal sludge.

^cBux *et al.* (2002) (based on wastewater sludge, adapted for drying from 20% ds to 90% ds).

^dZhao *et al.* (2010) (based on wastewater sludge).

^eGold (2017).

^fNikiema *et al.* (2013).

^gFakkaew *et al.* (2015a).

requirements are much higher than drying or other pelletizers, so a constant energy supply needs to be ensured.

HTC operates under high pressure, meaning that proper operation and maintenance are necessary to ensure safe operation. Therefore, this technology option should only be considered for contexts where the operation is performed by appropriately trained personnel. Additionally, treatment for the liquid by-products needs to be ensured, which is also more likely to be feasible on a centralized scale. Multiple variations on the process are currently in development, of which microwave heating reported the lowest energy consumption. The energy consumption of microwave HTC is 47–57% lower than HTC with an electric heating source (Afolabi & Sohail 2017a).

Pyrolysis of faecal sludge can reduce the sludge volume, but has a relatively high energy requirement. The quality of the fuel is not very high compared to other biomass fuels. Pyrolysis could be relevant for faeces from container-based sanitation models where the faeces is collected in portable containers at the user level, and regularly transported to

treatment by a designated collection service, but should not be pursued for faecal sludge.

A comparison of the environmental impact of pelletizing, carbonizing, and combining both processes to create fuel from passively dried faecal sludge has been performed by Egloff & Whett (2017). Their life cycle analysis results on global warming potential are summarized in Table 3 (in kg CO₂ equivalent/MJ end product). Compared to no processing (only drying on drying beds to 90% ds), pyrolysis increases greenhouse gas emissions by 733%, pelletizing by 46%, and the combination of the two processes by 938%. The impact of pyrolysis on global warming potential has also been investigated by Houillon & Jolliet (2005), who evaluated the environmental impact of pyrolysis (among other processes) with sewage sludge. Production of fuel through pyrolysis seems to have a higher environmental impact than non-carbonized fuels. HTC could potentially reduce greenhouse gas emissions by reducing drying time (Escala *et al.* 2013), which strongly affects greenhouse gas emissions (Houillon & Jolliet 2005; Escala *et al.* 2013).

Land area use does not have a large influence on environmental impact, but from an urban planning or faecal sludge management point of view, land area is a major point to consider (Egloff & Whett 2017).

All technologies for application with faecal sludge are currently in development on a laboratory-, bench-, or pilot-scale, meaning that it is not yet possible to provide a cost comparison. Future research should be focused on scaling up relevant technology options to scales relevant for treatment.

Technology selection

In conclusion, as illustrated in Figure 2, the selection of the fuel type will depend on: (1) the intended use of the fuel (e.g. combustion technology, user/handling requirements, and amount required); and (2) the properties of the input faecal sludge (e.g. level of stabilization, sand content, and moisture content). The intention of Figure 2 is to help identify suitable technology options, which must subsequently be evaluated for best fit in the local context (e.g. local capacity for electricity, land, and technical (operation and maintenance) requirements).

To start with, the (expected) characteristics of the input sludge must be determined. If quality or quantity of the input faecal sludge does not comply with user needs (e.g. if calorific value or quantity is too low), co-processing with other biowastes could be an option to improve the faecal sludge fuel. When there is no land area for drying, and operational safety can be ensured, HTC or LaDePa could be a solution, as both technologies can take high moisture sludge (20% ds) as an input. When the receiving combustion technology is not capable of handling high-ash fuels, adding another biomass resource could improve fuel quality and lower the ash fraction. For example, in faecal sludge char from pyrolysis, co-processing experiments with faecal sludge and sawdust showed that the calorific value decreased and the percentage of ash increased linearly with increasing fractions of faecal sludge (Mwamlima *et al.* 2017). Adding another biomass source is also a good way to increase end product volume to meet high volume demands of industrial consumers, provided that waste biomass is available in sufficient quantities for co-processing and at an affordable price.

The decision to char or not to char affects the fuel properties considerably and is, therefore, a critical factor. The ash in faecal sludge is concentrated during pyrolysis.

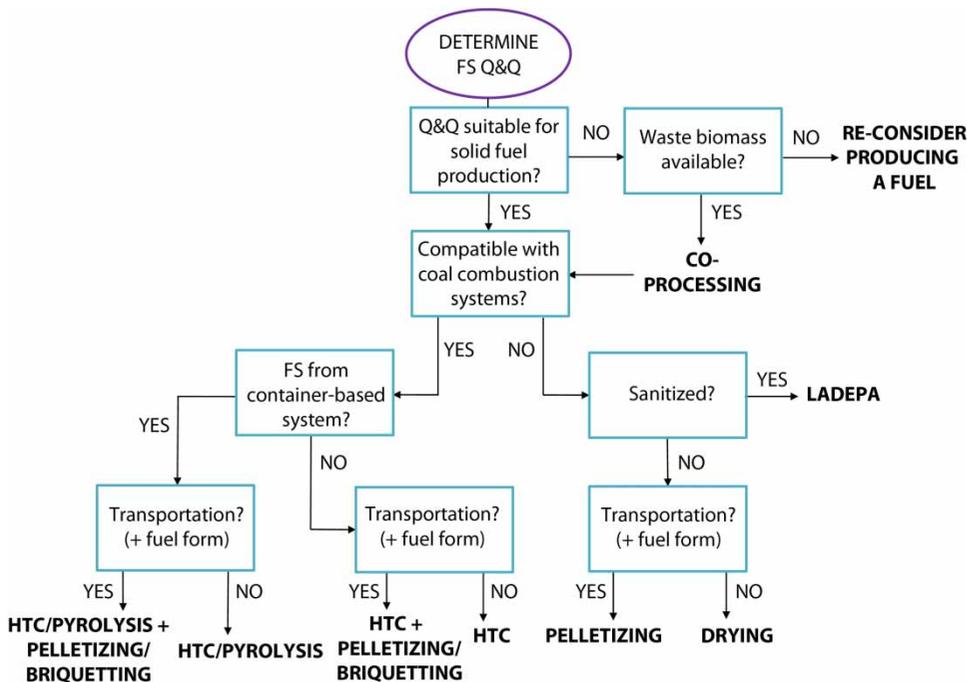


Figure 2 | Decision tree suggesting a decision basis for selecting appropriate technologies to produce a solid fuel from faecal sludge, starting from the quantities and qualities (Q&Q) of influent faecal sludge.

Typically, non-carbonized faecal sludge has a higher calorific value and lower ash content than pyrolysed sludge, which makes it distinct from other biomass. HTC, in contrast, produces hydrochar from faecal sludge with a higher calorific value than dry sludge. However, operational requirements do not make it a safe option in many situations. In cases where the desired end product should be compatible with coal or charcoal combustion systems and the receiving combustion technology is capable of handling high-ash fuels, carbonization is an option. Char is preferred over dried biomass for co-combustion with coal when very high-temperature combustion processes are desired (e.g. for steel or glass production), or when impurities in flue gas would be detrimental. In cement and brick kilns, co-combustion with dried biomass does not seem to pose a problem and is frequently practised (Zethraeus 2012). The quality of char from sources that are relatively unstabilized and have low sand content (e.g. faeces, or faecal sludge sourced from container-based systems) will be better than char from faecal sludge that typically comes into treatment plants. In most other cases, non-carbonized fuel should be favoured, as it is easier and less energy-intensive to produce.

Pelletization or briquetting is compatible with a range of moisture contents and sludge properties, and can also be used for co-processing with waste biomass. Both make the end product fuel more robust for transportation to customers and could be applied when the receiving combustion technology is compatible with compressed fuel.

The guidelines presented in Figure 2 fit within a greater framework of technology selection. Before deciding on a solid fuel as a resource recovery product, a market assessment should be conducted. Available quantities and qualities of the input faecal sludge should be assessed and Figure 2 can be used to generate suitable technology options. Subsequently, identified technologies should be evaluated based on local capacities and limitations.

FUTURE RESEARCH NEEDS

To get faecal sludge fuels into practice as rapidly as possible, research should focus on upscaling of the presented technologies. For practitioners, this is currently the greatest need. This includes extended pilot trials of different configurations of faecal sludge fuels in industrial kilns in collaboration with

industries, optimization of reactor dynamics in larger reactors, and testing business models for resource recovery-oriented faecal sludge management. At the same time, researching ways to improve fuel quality or quantity can help to build a more robust and desirable product, targeted at the needs of potential customers. Suggestions include investigating the removal of sand at treatment facilities, investigating drying methods that do not increase sand content (e.g. alternatives to sand drying beds or methods to reduce sand transfer from drying beds), or optimizing operating conditions for improved fuel production.

CONCLUSIONS

The key considerations for the use of faecal sludge as a dry combustion fuel are as follows:

- The work summarized in this paper has only been conducted at a laboratory- or pilot-scale. It is promising for full-scale implementations, but requires more resources prior to scaling up.
- In comparison to simple combustion of dried faecal sludge, pyrolysis is not as beneficial based on fuel quality and environmental impact.
- All types of resource recovery options should be considered based on the local context, prior to selecting end use as a solid fuel.
- Industry is a promising end user of faecal sludge solid fuels, based on consistent, large-scale demand; preventing pathogen transmission during handling; and capacity for reduced emissions.
- Forms of solid fuel need to be selected to be compatible with existing combustion technologies.
- Governments could improve public health by putting rules and regulations in place that enable safe resource recovery (e.g. solid fuel production stimulating the treatment of faecal sludge).

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