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Pyrolysis of faecal sludge and biomass waste for resource recovery in Kampala, Uganda

M. E. Koulouri, *[a] L. Owomuhangi,[b] Y. Lugali,[b] M. R. Templeton[a] and G. D. Fowler[a]

Globally, the rapid increase in non-sewered sanitation services is leading to the accumulation of large quantities of faecal sludge (FS) that need to be safely collected and treated. Pyrolysis is a promising technology for FS sterilisation and resource recovery, however, there is still limited knowledge on the properties and recovery potential of FS chars produced at scale. This study assessed the agricultural and solid fuel value of chars produced at an operating treatment plant in Uganda, that treats FS (from pit latrines and septic tanks) and local biomass waste (sawdust and bagasse). Results were compared with findings for laboratory-prepared excreta chars (from mixed or separated faeces and urine) to identify optimisation pathways *via* sanitation source control. The phosphorus content of FS chars was promising (4% P w/w), but nitrogen and potassium levels were relatively low compared to typical fertiliser requirements. Feedstocks from urine-diverting toilets could enable further nitrogen recovery from urine and maximise the total nutrient recovery potential. Heavy metal levels were below threshold values published in Uganda, although a need for regulatory guidelines specific to char-based fertilisers was identified. Outlier values were observed, highlighting the importance of regular quality control testing. Solid fuel briquettes prepared from carbonised FS and biomass waste were incorporated into the local market, mainly due to their slow burning properties and affordability, and despite their low calorific value compared to commercial standards (HHV = 12.5–16 MJ kg^{-1}). The high ash content of FS chars (~70% w/w) was the limiting factor for improved briquette quality, hence source control to limit inorganic contaminants (*e.g.* lining latrines) and urine diversion to separate organic and inorganic excreta streams were identified as suitable interventions to maximise the energy value of FS-derived briquettes (HHV = 20–22 MJ kg^{-1} possible for outputs of source-separating toilets mixed with biomass waste). This research provides novel field-based insights into FS pyrolysis in low-income settings, highlighting the importance of both strategic sanitation design and improved treatment efficiency to maximise resource recovery at scale.

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Water impact

Globally, more people use on-site sanitation than sewered connections, creating an urgent need for effective and sustainable faecal sludge management. This article advances knowledge of faecal sludge pyrolysis to support at-scale nutrient and energy recovery, addressing timely resource challenges in Uganda and beyond. Findings bridge fundamental research with real-world applications and can be used directly by WASH researchers and practitioners.

1. Introduction

The United Nations (UN) Sustainable Development Goal (SDG) 6 on "clean water and sanitation" calls for universal access to sanitation services, as well as adopting sustainable management practices for the faecal sludge (FS) that is being contained and collected.[1] Nevertheless, the current rate of progress is insufficient to achieve these targets and will require a fivefold increase to reach SDG 6 by 2030.[2] In least developed countries (LDCs) and isolated areas, a ≥15-fold increase in rate of progress is required.[3] This is driving a rapid increase in new on-site (non-sewered) sanitation services globally, due to their low cost, robustness and ability to be operated in areas with limited water resources.[4] Current knowledge suggests that safe FS management (FSM) solutions are successfully implemented if they can benefit communities in multiple ways, including capacity-building for recycling and recovery of resources.[5,6] Therefore, sustainable sanitation systems are directly or indirectly linked with various other resource management priorities and SDGs.

[a] *Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, UK. E-mail: maria.koulouri17@imperial.ac.uk*
[b] *Water For People Uganda, Plot 15 Lugogo By-Pass, Kampala, Uganda*

The connection between SDG 6 and SDG 2 ("zero hunger") has been well-established, making nutrient recovery a critical resource circularity priority, especially for phosphorus (P) and nitrogen (N).[7–10] Growing urban populations also create an increased demand for reliable and affordable fuels (SDG 7 – "affordable and clean energy"). For LDCs and low-/middle-income countries (LMICs) there is still a strong reliance on solid fuels, with 80% of the East African population relying on charcoal that is often derived from unsustainable forest management practices leading to deforestation.[11] Therefore, waste-derived fuels, including FS-derived briquettes, can be a valuable intermediate fuel during the global transition to clean energy.[12,13]

These parallel challenges of sanitation inequalities and resource scarcity, create an opportunity to combine waste and resource management objectives, by recovering valuable resources from FS. Pyrolysis – the thermochemical treatment of carbonaceous materials under oxygen-limited conditions – is a promising solution for combined FS treatment and recovery as it ensures pathogen sterilisation (temperature >300 °C) and offers several nutrient and energy recovery opportunities.[14–16] The solid output of the process, known as char (or "biochar" for biomass-based feedstocks), has been used in many sectors, including as a fertiliser and soil amendment, a solid fuel or an adsorbent.[17–19]

Currently, only a few full-scale pyrolysis FS treatment plants (FSTPs) exist around the world, hence the critical interpretation of data for real-world FS char samples remains challenging.[20] The high variability of FS composition (*e.g.* FS from pit latrines *vs.* septic tanks or FS from urine-diverting *vs.* mixed toilets) intensifies the uncertainty of end-product characteristics.[21,22] For LMICs and LDCs, operational challenges (*e.g.* unstable electricity supply) make the adoption of traditional carbonisation kilns more attractive than commercially available pyrolysis systems, further broadening the variability of operational conditions and hence, end-product characteristics.[23] While previous studies have highlighted the importance of source control to enable consistent resource recovery from human excreta, the quantification of these benefits remains challenging for highly variable FS feedstocks produced under field conditions.[24,25]

The aim of this study was to assess the agricultural and solid fuel value of chars produced at an operating FSTP in Kampala, Uganda, that treats FS and biomass waste materials. For the first time, the comprehensive characterisation of FS chars was combined with a focused comparison against laboratory-prepared excreta chars, to identify opportunities for improved resource recovery at scale. The specific study objectives were to: 1) determine the agricultural value of FS chars produced during two years of FSTP operation (2022–2023), based on established standards (*e.g.* International Biochar Initiative, Uganda National Bureau of Standards); 2) characterise solid fuel briquettes produced from carbonised FS and biomass waste, at the FSTP; and 3) compare these results against the baseline properties of excreta-derived chars produced under laboratory conditions (from mixed or separated faeces and urine)[25] to quantify optimisation pathways *via* source control. The findings of this research contribute to the currently limited knowledge of FS char characteristics under real operational variability and market deployment potential, which is essential for the technological development of full-scale FS pyrolysis solutions.

2. Materials and methods

2.1 Treatment plant location and faecal sludge origin

The sampling location for this study was a FS carbonisation (*i.e.* very slow pyrolysis intended for solid char production) and briquette production plant established by Water For People inside the Lubigi Sewage Treatment Plant in Kampala, Uganda, in partnership with the National Water and Sewerage Corporation (NWSC) of Uganda and Kampala Capital City Authority (KCCA). The plant treats a combination of FS and sewage with daily capacities of 400 m^3 and 5000 m^3 respectively. Treatment stages for FS include a screening and grit removal unit, thickening tanks and unplanted drying beds.[26] The origin of the FS is a combination of pit latrines (lined and unlined) and septic tanks located in Kampala settlements (approximate ratio 1 : 2 v/v pit latrine : septic tank sludge).[27] Properties of the dried FS relevant to this study (thermally relevant properties and concentrations of major nutrients) are shown in Table 1. Analysis of uncarbonised FS samples was conducted by Makerere University in Kampala (College of Natural Sciences, Kampala Uganda).

2.2 Carbonisation and briquette production

Carbonisation was conducted using traditional kilns consisting of modified air-locked metallic drums, as shown in Fig. 1a. The dried FS and other locally sourced biomass waste (bagasse [BG], sawdust [SD]) were used as feedstocks for carbonisation. Sawdust (*i.e.* wood residues) was sourced from carpentries and furniture workshops in Kampala and was air-dried prior to carbonisation (typical moisture content = 17.5%). Bagasse (*i.e.* by-product of sugarcane processing)

Table 1 Proximate analysis, CNS and nutrient content of dried faecal sludge (FS) from the Lubigi Sewage Treatment Plant in Kampala, Uganda (on a dry weight basis) (n = 3)

VM[a] (%)	FC[b] (%)	Ash (%)	C (%)	N (%)	S (%)	P[27] (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
57.1 (± 14.0)	7.2 (± 0.7)	35.7 (± 13.8)	22.8 (± 0.6)	2.3 (± 0.4)	0.14 (± 0.0)	26.9 (± 7.9)	6.0 (± 0.4)	18.9 (± 4.1)	3.3 (± 0.2)

[a] VM = volatile matter. [b] FC = fixed carbon.

Fig. 1 (a) A metallic drum carbonisation kiln in use; (b) the carbonisation initiation with wood as a start-up fuel; (c) the produced faecal sludge char (ground); (d) the briquette extruder machine; and (e) the produced briquettes on drying racks (Lubigi Wastewater Treatment Plant, Kampala, Uganda).

was sourced from Lugazi Sugar Factory and was sun-dried prior to carbonisation (typical moisture content ≤15%).

The carbonisation process was initiated with available start-up fuels (*e.g.* wood, briquettes) (Fig. 1b). Once the dry feedstock was placed in the drum, the kiln was air-locked, samples were left to carbonise overnight and the char was collected the next morning (Fig. 1c). Temperature readings were taken periodically, using a UNI-T portable digital thermometer with a thermocouple attached. Due to the limited operational control possible in these types of traditional kilns, the temperature during carbonisation varied, typically between 300–400 °C based on manual thermometer readings. The effective highest heating temperature (HHT) reached was estimated based on the post-treatment weight loss onset temperature and was 360–390 °C for all (homogenised) samples (see characteristic thermogravimetric analysis curve in Fig. S1, SI). Measures to minimise process variability included: (i) consistent feedstock mass, particle size and moisture content; (ii) overnight carbonisation to ensure sufficient heating of the whole feedstock mass; and (iii) consistent start-up fuel input quantity.

For the briquette production, ground char samples (FS, BG, SD) were combined with binders (clay and molasses) before mechanical extrusion. The choice of binders was based on local availability and previous research,[28,29] and their mixing ratio typically was: 3–4 L molasses (to improve physical and combustion properties), 6–10 kg clay (to improve strength and increase burn time), 40 L water and 200 kg char. Briquettes were produced using a screw press extruder and were placed on drying racks to air dry (Fig. 1d and e). Preliminary mechanical strength tests (*i.e.* assessment of impact following drop test from 1.1 m, relative to a commercial charcoal briquette) were conducted on-site to ensure all briquettes assessed in this study have sufficient durability for commercialisation.

2.3 Sampling and experimental design

After each batch of carbonisation, char samples were ground into a fine particle size (typically <2 mm) (Fig. 1c) and homogenised before sample collection. To ensure samples were representative, carbonisation runs for each feedstock type were repeated three times, on different days, and all analysis was conducted in triplicate. Two sampling campaigns were carried out, in February 2022 and May 2023. During the 2nd sampling campaign, three samples (≥300 g) were collected and analysed for each run to minimise the effect of outliers on statistical power (*i.e.* 3 samples on-site × 3 laboratory sub-samples = 9 replicates × 3 runs) (Fig. S2, SI).

Locally available commercial charcoal dust (CD) was used as the baseline for the assessment of char fuel properties and briquette characteristics. Briquette production and sampling were also conducted in triplicate. The detailed description of produced char and briquette samples is shown in Table S1 (SI). Sample names for briquettes are referred as FS : X r1 : r2, where X is the biomass type (BG, SD, CD) and r1, r2 are the mixing ratios for FS and biomass materials, respectively.

2.4 Laboratory-scale pyrolysis of human excreta samples

Samples of source-separated human faeces (SSF) and urine were separately collected at Imperial College London from 12 volunteers over 4 months (September to December 2021) as described in a previous study by Koulouri *et al.*[25] Mixed urine and faeces samples (MUF) were prepared by blending urine samples (stored at 4 °C) and raw faeces at a ratio of 1 g : 10 ml (faeces : urine), representing the expected ratio of daily excretion.[30,31] The SSF and MUF samples were homogenised and combined into composite samples. Slow pyrolysis was carried out on a rotary furnace (Carbolite, UK) purged with N_2 (1.5 L min^{-1}). The experiments were conducted at three HHTs (450, 550, 650 °C) at a heating rate of 10 °C min^{-1} for 30 min, based on preliminary tests and previously published results on optimal pyrolysis conditions.[25]

2.5 Analytical methods

Experiments were conducted at the Roger Perry Laboratory (Imperial College London, UK) to determine the nutrient and heavy metal content of FS and human excreta chars, as well as the solid fuel characteristics of all available chars (FS, BG, SD, CD, SSF, MUF) and briquettes samples.

Analysis of the inorganic constituents of char samples (nutrients and heavy metals) was performed by ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) on an Avio 500 (PerkinElmer, USA), following acid digestion, as described by Koulouri *et al.*[25] Proximate analysis was conducted for the determination of the moisture content, volatile matter, fixed carbon and ash content, following standard method ASTM D7582-15[32] as adapted by Krueger *et al.*[21] for implementation by thermogravimetric analysis. The higher heating value (HHV) was determined by bomb calorimetry, following standard method ASTM D5865/D5865M-19[33] on a 6100 Calorimeter (Parr, USA). CHNS analysis was performed on a ThermoScientific Flash Smart Elemental Analyzer according to BS EN ISO 16948:2015.[34]

2.6 Statistical analysis

For the analysis of inorganic constituents of char samples, the occurrence of outliers was observed, and hence median values are presented instead of the arithmetic mean. The variance of FS char sample characteristics between the two sampling periods (February 2022 and May 2023) was investigated using the non-parametric Mann–Whitney U test. For the investigation of thermal properties of char and briquette samples, composite homogenised samples were used (FS, BG, SD, CD, SSF, MUF) and hence the arithmetic mean and standard deviation values are presented. Results were analysed by one-way ANOVA to assess the influence of feedstock type on char/briquette properties (0.05 significance level).

2.7 Ethical approvals

Approvals and permissions for the collection of human excreta samples used in this research project were obtained *via* the Imperial College Research Governance and Integrity Team (ref. no. 21IC6817) and the Imperial College Healthcare Tissue Bank (licence: 12275) [supported by the National Institute for Health Research Biomedical Research Centre based at Imperial College Healthcare NHS Trust and Imperial College London]. Informed consents were obtained from all human participants of this study.

3. Results and discussion

3.1 Agricultural value

3.1.1 Nutrient content. Agricultural uses of char-based fertilisers and soil amendments are widely recognised as a primary resource recovery objective for FS, due to the inherently high nutrient content of human excreta that further concentrates in the char fraction.[35,36] The nutrient content of all char samples produced in Uganda is shown in Fig. 2 for the two sampling periods and compared against baseline SSF/MUF chars produced under laboratory conditions in the UK.[25]

The N, P, K and Mg content of chars produced in Kampala was relatively consistent for both periods of sampling (see statistical analysis results in Table S2, SI), although outliers were observed, highlighting the importance of comprehensive quality control testing.[37] Calcium exhibited the highest variability between sampling periods, which may be influenced by dietary factors[38] and the diverse types of containment facilities found in Kampala, including septic tanks and pit latrines that may be lined or unlined (*i.e.* soil inputs in unlined latrines can introduce further Ca-containing compounds).[28,30,39] Based on on-site observations in Kampala and the observed differences compared to laboratory samples, on-site sampling may yield extreme outliers due to feedstock contamination, inadequate homogenisation before treatment or fluctuations in feedstock characteristics (*e.g.* sludge age) and treatment conditions (*e.g.* temperature and oxygen elimination). Multiple samplings are recommended for FSTP testing to detect outliers and observe statistically significant differences in nutrient content.[37]

The median P value of 39 g kg^{-1} is significantly higher than that of animal manure and other commonly used organic fertilisers, showing promise for agricultural applications.[40,41] Nevertheless, P concentrations were lower than in SSF/MUF chars, likely due to the inclusion of additional waste materials in traditional on-site sanitation facilities (*e.g.* sanitary products, toilet paper, household solid waste), as well as the variability of operating conditions during treatment (*e.g.* lower temperature reached during pyrolysis, reducing the relative content of inorganics in the char).[42,43] Separation of soluble nutrients during upstream FSTP stages (*e.g.* thickening) can also lower the nutrient concentrations of FS chars.[44]

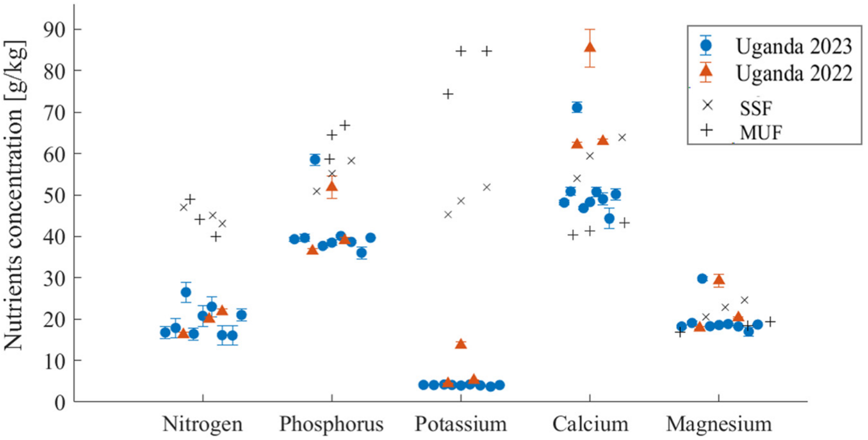

Fig. 2 Nutrient (N, P, K, Ca, Mg) concentrations (g kg^{-1}) of FS chars produced in Uganda in 2022 and 2023, and chars produced from source-separated faeces (SSF) and mixed urine and faeces (MUF) as presented in Koulouri *et al.*[25] Results are on a dry weight basis. Error bars denote the standard deviation between sub-samples (n = 3).

The FS chars were low in N (median value 19 g kg^{-1}), meaning that additional N fertilisation would likely be required for agricultural applications.[45] Urine diversion followed by combined applications of char and urine (typical N content 5000–7000 mg L^{-1}), or char enrichment with urine-derived nutrients could significantly boost the N content of FS-based fertilisers.[36,46] For K, a difference of multiple magnitudes can be observed between chars produced in Uganda and those produced in the laboratory (in the UK) from pure human excreta. This gap may be attributed to dietary nutrient deficiency factors as the occurrence of K scarcity in East African soils has been reported in various instances.[47,48] Therefore, the consideration of local and/or regional particularities when comparing results from different studies is essential, as potential differences in feedstock composition are magnified for the concentrated char fraction.[49,50] For Mg, no statistically significant differences were observed between FS and excreta-derived chars.

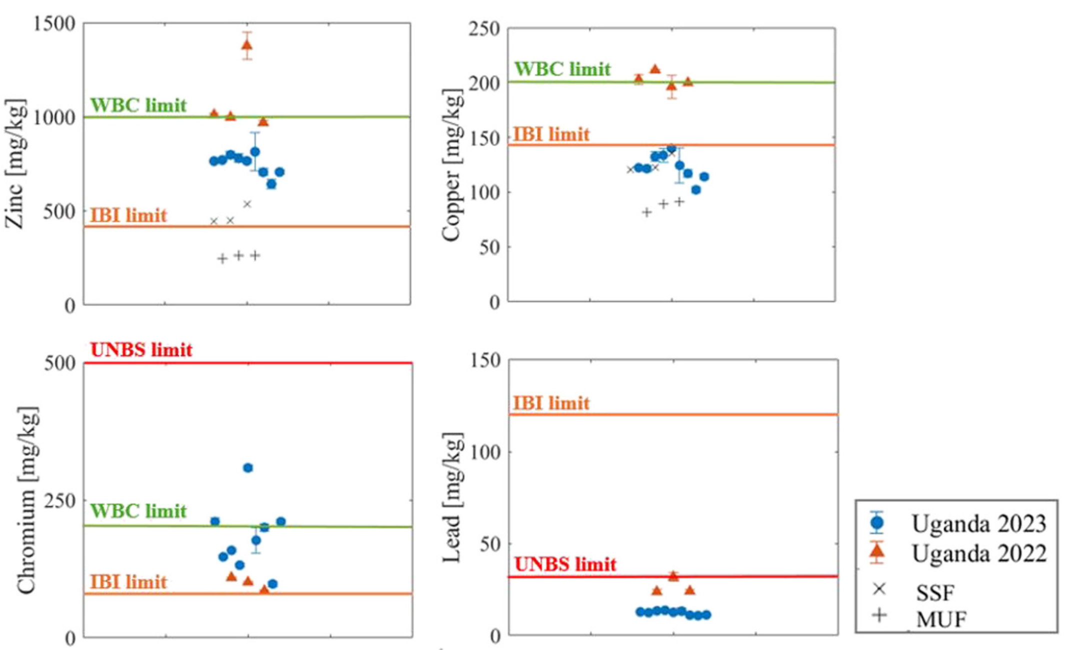

Fig. 3 Heavy metal (Zn, Cu, Cr, Pb) concentrations (mg kg^{-1}) of FS chars produced in Uganda (2022, 2023) and chars produced from source-separated faeces (SSF) and mixed urine and faeces (MUF) as presented in Koulouri *et al.*,[25] with reference to limit values provided by the International Biochar Initiative (IBI),[51] the World Biochar Certificate (WBC)[37] and indicative Ugandan standards (UNBS).[52] Results are on a dry weight basis. Error bars denote the standard deviation between sub-samples (n = 3). For SSF and MUF samples, Cr and Pb values were below the detection limit (<1 mg kg^{-1}).

Overall, the findings confirm the potential agricultural value of FS chars, while bringing light to the requirement for comprehensive quality control and homogenisation to ensure consistent feedstock properties and minimise the effect of outliers. Improving the reliability of char fertiliser value will be vital for upscaling of resource recovery applications.[43] Based on the comparison with pure human excreta samples, the implementation of container-based or urine-diverting facilities to accommodate future sanitation infrastructure would provide an opportunity to minimise contamination at source and maximise the NPK content of FS-derived chars.[25,31] Existing FS sources from traditional on-site containment facilities remain a valuable nutrient-rich material that is deemed suitable for nutrient recovery *via* pyrolysis, particularly for phosphorus.

3.1.2 Heavy metal content. The heavy metal content of FS chars from Kampala is shown in Fig. 3, also with reference to SSF/MUF excreta-based chars, and threshold values from international biochar standards and national standards in Uganda for phosphate fertilisers.[37,51,52] Variability among samples and between the two years of sampling was observed for all detectable trace elements (see statistical analysis results in Table S3, SI), suggesting that heavy metal testing should be repeated on a regular basis at FSTPs producing chars for agricultural uses.

Where limit values for heavy metals are set by the Uganda National Bureau of Standards (UNBS), specifically about lead (Pb) and chromium (Cr), these were satisfied for all samples, supporting agricultural applications of FS char in Uganda.[52] Other trace elements controlled by the UNBS, including cadmium (Cd), were below the detection limit (<1 mg kg^{-1}) for all samples tested in this study. For zinc (Zn) and copper (Cu), while no relevant Ugandan standards were found, measured values complied with the maximum allowed values suggested by the International Biochar Initiative (IBI),[51] but exceeded the stricter limits of the IBI range (shown in Fig. 3). Guidelines from the World Biochar Certificate (WBC) on maximum allowed values were generally met, but outlier values were identified.[37] Overall, results correspond well to literature findings reporting that Zn and Cu are potential elements of concern for excreta-based chars.[20,25,53]

Currently, local guidance in Uganda – and many other countries – is not specific to char fertilisers and only provides thresholds for some of the heavy metals identified in char samples.[37,52] Therefore, there is still a need to define comprehensive regulatory guidelines for heavy metal safety of char fertilisers, especially in countries where their use is becoming increasingly common. The WBC and IBI recommendations, as a compilation of the maximum allowed values for various countries (including Australia, Canada, several EU countries, the UK and the USA), can be used as guidance rather than requirements designed for applications in other countries/regions.[54] It is also worth noting that the relative rigour of individual standards is inconsistent, *i.e.* the IBI has a stricter acceptable limit for Cr, but the UNBS has a stricter limit for Pb, potentially to address locally relevant soil properties. Interestingly, some countries have started to introduce limits based on the nutrient-to-heavy-metal ratio, rather than absolute heavy metal concentrations.[37] This approach is suitable for concentrated char fertilisers that may require smaller application rates compared to compost or other organic fertilisers.

Results for human excreta samples were generally lower than the FS chars, suggesting that elevated values in FS are not attributable to excreta but additional waste discarded in on-site sanitation facilities (*e.g.* plastic waste, household chemicals, batteries).[55] It has been previously reported that human excreta contain fewer heavy metals than FS and sewage sludge, supporting the hypothesis that the purer the source of human excreta, the lower heavy metal exposure risks can be expected.[56,57] Biomass cover materials added in on-site toilets (*e.g.* sawdust, coconut husk) would further dilute the heavy metal concentration of sanitation outputs and recovered products.[20] Therefore, better source control and raising awareness of sanitation users to minimise additional waste being discarded in toilets may be successful interventions to decrease heavy metal content where needed.[58]

3.2 Solid fuel value

The solid fuel characteristics of char samples were of interest on account of the fluctuating prices of charcoal and the high demand for waste-derived solid fuels in Kampala and other urban centres of LDCs and LMICs.[28,59] Thermally relevant properties of locally produced chars from dried (homogenised) FS, bagasse (BG) and sawdust (SD), as well as locally purchased commercial charcoal dust (CD) and human excreta samples (produced in the UK) – as baselines for comparison – are presented in Table 2 (ANOVA results in Table S4, SI).

The produced FS chars had high ash content (~70%) and a median HHV of 6.4 MJ kg^{-1}; approximately half the HHV recorded for chars from pure human excreta (~13 MJ kg^{-1}). The deviation from pure excreta-based chars confirms that the ash content is derived from other inorganic contaminants entering sanitation systems at the source (*e.g.* by users or during containment in unlined and partially-lined latrines) or during treatment.[21,25,60] Where source control is feasible, the encouragement of lining latrines to minimise inorganic contamination can significantly improve the fuel value of FS-derived products. These results also confirm the need for co-treatment with additional biomass materials of higher calorific value to produce solid fuels that can compete with commercial standards (see section 3.2.1).[61] As an indication, the baseline CD tested in this study contained ~20% ash and had a median HHV of 22.4 MJ kg^{-1}, almost four times higher than for FS chars.

Carbonised bagasse appears to have good fuel properties, with similar characteristics to commercial charcoal (HHV 20.7 MJ kg^{-1}) and can therefore realistically be investigated as a potential additive for briquette production. The sawdust

Table 2 Proximate analysis, CHNS and calorific value (HHV) results for char samples produced from faecal sludge (FS), bagasse (BG), sawdust (SD) and charcoal dust (CD) (as received basis), and SSF, MUF samples from Koulouri *et al.*[25] (produced at 450 °C) as a baseline for comparison (on a dry basis) (n = 3)

	MC[a] (%)	VM[b] (%)	FC[c] (%)	Ash (%)	C (%)	H (%)	N (%)	S (%)	HHV[d] (MJ kg^{-1})
FS	3.6 ± 0.9	19.6 ± 1.9	7.9 ± 1.8	68.9 ± 2.0	17.4 ± 0.5	1.6 ± 0.2	1.9 ± 0.3	0.8 ± 0.5	6.4 ± 1.1
BG	3.0 ± 0.8	31.1 ± 0.7	45.4 ± 0.9	20.5 ± 1.4	55.3 ± 2.1	3.2 ± 0.1	0.4 ± 0.1	0.2 ± 0.0	20.7 ± 0.9
SD	4.2 ± 0.7	29.8 ± 1.4	34.4 ± 1.2	31.6 ± 1.2	53.3 ± 2.4	4.6 ± 0.6	0.3 ± 0.1	0.4 ± 0.1	18.1 ± 2.1
CD	4.4 ± 0.6	19.6 ± 0.6	56.2 ± 1.4	19.8 ± 1.7	58.5 ± 0.9	2.4 ± 0.5	1.1 ± 0.2	0.2 ± 0.1	22.4 ± 1.6
SSF		24.4 ± 1.7	43.0 ± 0.7	32.6 ± 0.7	50.9 ± 0.6	3.3 ± 0.0	4.7 ± 0.0	1.2 ± 0.0	20.3 ± 0.1
MUF		27.0 ± 0.1	22.9 ± 0.6	50.1 ± 0.6	33.1 ± 0.6	1.9 ± 0.1	4.9 ± 0.0	2.0 ± 0.1	13.3 ± 0.3

[a] MC = moisture content. [b] VM = volatile matter. [c] FC = fixed carbon. [d] HHV = higher heating value.

char samples had slightly lower calorific value compared to bagasse (18.1 MJ kg^{-1}), although this can be partly attributed to operational challenges during carbonisation, based on on-site observations (*e.g.* high initial moisture content (MC)). The final MC was similar for all carbonised samples and in line with recommendations from the Food and Agriculture Organization (FAO) to avoid breakage and production of char fines during burning (MC < 10%).[62] Biomass-derived chars had significantly lower N and S content compared to FS and human excreta (Table 2) and therefore, their addition in briquettes can be expected to decrease NOx and SOx emissions during burning, even at high combustion temperatures where such emissions are more likely to form.[13,63]

3.2.1 Briquette characteristics. Fig. 4 shows the calorific value (HHV) of briquettes produced from different mixtures of carbonised FS and available biomass materials, relative to an indicative commercial standard (17 MJ kg^{-1}) and the value expected for commercial charcoal according to FAO standards (22 MJ kg^{-1}).[62,64] It is apparent that the high ash content, and hence low calorific value of FS (Table 2) has a negative effect on briquette quality, with briquettes containing 50% FS not exceeding HHVs of 15 MJ kg^{-1}. For briquettes containing 40% FS, the maximum calorific value was 16 MJ kg^{-1} for FS : CD 40 : 60 and 14.5 MJ kg^{-1} without the presence of any commercial charcoal (for FS : BG 40 : 60). These values are below the minimum commercial standard (17 MJ kg^{-1}), highlighting that the high ash content of FS is a critical limiting factor for solid fuel production (see section 3.2.2 for ash–HHV correlation).[64]

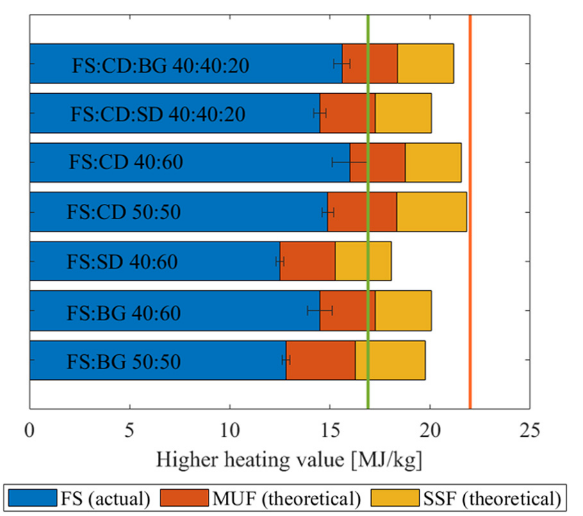

Fig. 4 Higher heating values (MJ kg^{-1}) of briquette samples in comparison to the minimum commercial standard (17 MJ kg^{-1}) (vertical green line)[64] and the value expected for commercial charcoal, according to FAO standards (22 MJ kg^{-1}) (vertical orange line).[62] The naming convention is described in Table S1. Theoretical values for briquettes prepared with SSF/MUF samples pyrolysed at 450 °C (instead of FS) are also included.[25] Error bars denote the standard deviation of measured values (n = 3).

Despite these results, preliminary assessments of user satisfaction conducted by Water For People were positive, bringing attention to the importance of affordability and accessibility as defining factors for user satisfaction, often despite technical deficiencies.[65] The slow burning properties and low cost of FS-containing briquettes make them an attractive alternative for communities that heavily rely on solid fuels, such as wood and wood-derived charcoal.[66] CHNS analysis (Table 3) showed low N and S content for all briquette samples (<1.5% and ≤0.2% respectively), confirming that low NOx and SOx emissions are expected during burning of FS : biomass fuels.[57,67] The C content and HHV were higher for briquettes containing BG compared to SD, which can be attributed to the lower ash and moisture content of BG char samples (see Table 2). The low H content of the briquettes indicates that air-drying is sufficient to remove moisture after binder addition.

Given the high demand for solid fuel briquettes, it is essential that efforts for further optimisation of product quality continue, both at the treatment and briquette production level (operational parameters *etc.*) and *via* source interventions. Findings from previous research[25] can be applied here to estimate the theoretical HHV values if FS from pit latrines and septic tanks was substituted with a) human excreta from enclosed mixed toilets such as container-based sanitation (CBS) toilets (*i.e.* here represented by MUF-derived chars); or b) human faeces from source-separating toilets (*i.e.* here represented by SSF-derived chars). Results are included in Fig. 4 and show that source interventions can have a significant positive effect on the fuel value of produced briquettes. When assuming sludge from

Table 3 CHNS analysis of briquette samples produced from different combinations of faecal sludge (FS), bagasse (BG), sawdust (SD) and charcoal dust (CD) (n = 3). Naming convention described in Table S1 (SI)

	C (%)	H (%)	N (%)	S (%)
FS[a] : CD[b] : BG[c] 40 : 40 : 20	44.7 ± 0.5	1.5 ± 0.2	1.0 ± 0.2	0.1 ± 0.1
FS : CD2 : SD[d] 40 : 40 : 20	39.4 ± 1.5	2.3 ± 0.1	1.1 ± 0.1	0.2 ± 0.2
FS : CD 40 : 60	48.5 ± 1.6	1.9 ± 0.2	0.9 ± 0.1	0.1 ± 0.1
FS : CD 50 : 50	43.3 ± 0.9	1.9 ± 0.1	1.7 ± 0.3	0.1 ± 0.0
FS : SD 40 : 60	36.6 ± 1.8	2.8 ± 0.3	1.0 ± 0.1	0.2 ± 0.0
FS : BG 40 : 60	42.1 ± 0.9	2.0 ± 0.4	1.3 ± 0.1	0.1 ± 0.0
FS : BG 50 : 50	33.7 ± 1.3	2.2 ± 0.5	1.1 ± 0.1	0.1 ± 0.0

[a] FS = faecal sludge. [b] CD = charcoal dust. [c] BG = bagasse. [d] SD = sawdust.

enclosed containment systems where no other additives except for human excreta and biomass materials are added, almost all briquettes would have HHV values >17 MJ kg^{-1} (Fig. 4). Further improvements were observed for the urine diversion scenario, in which case briquettes with similar HHV to commercial charcoal (22 MJ kg^{-1}) can be potentially produced from human excreta. These results suggest that outputs of CBS toilets are more suitable for solid fuel production applications, whereas existing high-ash FS sources from traditional on-site containment facilities in Kampala may be better suited to agricultural applications (see section 3.1).

3.2.2 Ash–HHV correlation analysis. While the HHV analysis requires specialised equipment, investigating correlations with relatively simple measurements can further support FSTP operations. Several studies have reported a strong correlation between char ash content and calorific value, although it has not been confirmed whether the same correlation parameters apply to FS-derived briquettes.[12,15] Results from previous studies have been plotted in Fig. 5 and used for data validation.[12,18,20] The values measured in this study for FS chars fall within the 95% confidence interval of the correlation calculated from previous studies (eqn (1)). Ward *et al.*[12] also provided an equation to calculate HHV based on the CHNSO content of chars, although that is a more complicated measurement requiring specialised laboratory facilities. Krueger *et al.*[21] calculated an HHV–ash correlation for uncarbonised FS which, notably, is different to the one calculated for char samples, but may be suitable for initial screenings of feedstock materials.

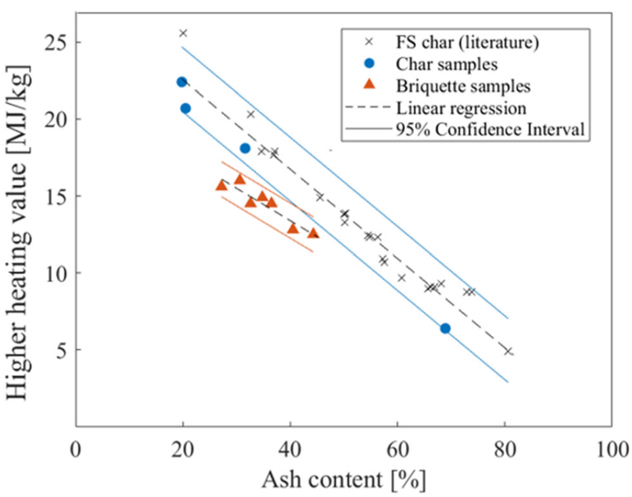

Fig. 5 Correlation between higher heating value (MJ kg^{-1}) and ash content (%) of char and briquette samples, with the inclusion of literature values for FS char samples.[12,18,20,25]

In this study, the correlation between ash content and HHV value was also investigated for the produced briquette samples (Fig. 5 and eqn (2)). While a linear correlation was also observed, this was different to the relationship previously identified for char samples (eqn (1)), due to the presence of additional binding materials in the briquettes (clay and molasses) that alter their composition compared to the chars they originate from. Given the limited sample size of briquettes available in this study, it is recommended that the relationship presented in eqn (2) is validated by future studies on FS-derived briquettes. Nevertheless, the local context, kiln design, operational conditions, types of binders and individual feedstock properties need to be considered on a case-specific basis.[68]

$$\mathrm{HHV_{char}}\ [\mathrm{MJ\ kg^{-1}}] = -0.2901 \times \mathrm{AC}\ [\%] + 28.3392\ (R^2 = 0.97) \quad (1)$$

$$\mathrm{HHV_{briquette}}\ [\mathrm{MJ\ kg^{-1}}] = -0.2104 \times \mathrm{AC}\ [\%] + 21.8087\ (R^2 = 0.87) \quad (2)$$

where, $\mathrm{HHV_{char}}$ and $\mathrm{HHV_{briquette}}$ are the higher heating values (MJ kg^{-1}) for char and briquette samples respectively; and AC (%) is the ash content of the samples.

Overall, the high ash content of currently available FS sources is identified as a significant barrier for solid fuel production that needs to be addressed *via* source control. Efforts to minimise the ash present in FS will be critical to optimise resource recovery, including lining latrines to limit the entry of soil or other inorganic contaminants at the source (see Table 2), and avoiding the use of sand in drying beds at FSTP-level. In terms of interventions at the toilet-level, both urine diversion and biomass addition can significantly decrease FS ash content, hence increasing the calorific value of produced briquettes (see Fig. 4).

3.3 Practical recommendations

From an operational perspective, several practical recommendations for the optimisation of FSTPs in LDCs and LMICs can be drawn from this study. A main challenge identified for traditional kilns was the high residual volatile matter of produced chars (≥20% as shown in Table 2), confirming that the temperature reached inside the metallic drum kiln was insufficient to complete carbonisation reactions (*i.e.* not exceeding 450 °C).[14,45] While briquettes with high volatile matter can ignite easily, their burn time is lower than fully carbonised fuels and they generate more smoke during their use, negatively affecting air quality, particularly for indoor activities such as cooking.[63] Therefore, the completion of carbonisation reactions is essential to recover "smokeless" fuels that are safe for indoor use. Based on findings presented in Koulouri *et al.*,[25] pyrolysis between 450–500 °C is recommended to ensure complete carbonisation of excreta-derived materials, without compromising the calorific value at higher treatment temperatures (>500 °C).[14,69] The same principle applies to chars intended for agricultural use, as the residual volatile matter corresponds to readily labile organic compounds that may be leached after application to soil.[70–72] For agricultural uses, treatment temperatures between 500–600 °C are recommended.[14,18,25]

In terms of the kiln design, while traditional kilns are a realistic solution for low-resource settings, targeted modifications are recommended to allow for accurate temperature monitoring and control (*e.g.* installation of thermocouples inside the kiln), and maximise operational consistency.[13] Further measures could include the incorporation of insulation materials to increase the highest heating temperature reached inside the kiln, as well as improved heat convection mechanisms (*e.g.* gas recirculation). Maintaining an oxygen-free or oxygen-limited environment inside the kiln is also essential. Efforts to effectively "air-lock" the kiln from the onset of the process are recommended to avoid partial combustion (ashing) of the feedstock during treatment and maximise char and briquette calorific value. Further quantitative briquette strength testing (*e.g.* compressive strength test) is also recommended, ideally to be performed on-site or at local laboratories, to optimise mechanical strength and ensure durability.

Wider environmental issues that need to be addressed include the installation of emission control systems and the optimisation of process energy efficiency.[13,73] Ideally, the thermal energy of produced gases should be used to (partially) replace external heating requirements, as well as for pre-treatment steps (*e.g.* thermal drying).[18,74] In LDCs and LMICs, solid fuels are often used as the heating source of traditional kilns, in which case the use of recovered products (*e.g.* waste-derived briquettes) should be prioritised over the use of wood or commercial charcoal. Improving the energy efficiency and environmental performance of FS pyrolysis applications will be essential for upscaling and to ensure their long-term sustainability (both environmental and financial). Detailed environmental, social and technoeconomic assessment studies of pilot and full-scale FS pyrolysis plants will support wider adoption and social acceptance.[75]

Apart from technical indicators, an understanding of the context-specific market landscape is also critical.[65] For example, in Kampala, the need for affordable solid fuels is driving demand for waste-derived briquettes despite the high ash content of the currently available FS feedstocks. Source control is therefore particularly important when the recovery objective precedes the feedstock selection. A different market landscape can be expected in rural areas, where the higher demand for recovered nutrients from farmers may create added incentives for fertiliser production.[76] Understanding the local sanitation landscape (*i.e.* prevalence of lined or unlined latrines, septic tanks, urine diverting toilets or other on-site sanitation facilities) is also critical, as different feedstocks will have different recovery potential.[21] For example, given the correlation between ash content and fuel quality (Fig. 5), FS from unlined latrines with high inorganic contamination should be diverted from fuel recovery applications, but may be desirable for agricultural uses, subject to suitable heavy metal content.

Ultimately, changing the perception of sanitation systems to a resource-focused paradigm requires the participation of local stakeholders (*e.g.* to co-design locally appropriate FSM schemes), but this is admittedly easier when the technical feasibility of recovering safe, affordable and sustainable products is consistently proven at-scale.[77,78] The findings of this study can inform strategic sanitation planning and regulatory development in Uganda, or other countries with similar sanitation/resource landscapes (*e.g.* setting nutrient recovery targets, developing standards of practice and adopting local heavy metal thresholds for FS-derived chars). Future research can include policy-focused analyses to develop evidence-based engagement strategies between technical stakeholders, communities and policymakers.

4. Conclusions

This study investigated the operation and products of a carbonisation FSTP located in Kampala, Uganda where FS and biomass waste are treated to produce soil amendments and solid fuel briquettes. The following conclusions can be drawn from this research:

• The agricultural value of FS chars produced in Uganda was promising, particularly for P recovery (4% w/w median P content), but feedstocks from urine-diverting toilets would allow further N recovery from urine and maximise the total nutrient recovery potential.

• Heavy metal levels were below local limits (where available) but exceeded some international guidelines for char fertilisers.

• Solid fuel briquettes prepared from carbonised FS and biomass waste were incorporated into the local market, mainly due to their slow burning properties and affordability, and despite their lower calorific value compared to commercial standards (HHV = 12.5–16 MJ kg^{-1}).

• Faecal sludge chars with high ash content (~70%) were deemed suitable for agricultural applications but can be challenging for solid fuel production due to the strong correlation between ash content and calorific value (R^2 = 0.97). The control of FS ash content will be critical for the viability of fuel recovery applications.

• Urine diversion was identified as a promising source control strategy to maximise the energy value of FS-derived briquettes (HHV = 20–22 MJ kg^{-1} possible for outputs of source-separating toilets).

• Both feedstock properties and operational conditions during treatment determined the final quality of recovered products and their suitability for different resource recovery options. Comprehensive sampling protocols are essential for the assessment of FSTP operations due to the observation of outliers for all parameters of interest.

• Technical improvements of traditional carbonisation kilns are recommended to increase (and accurately monitor) the highest heating temperature reached, and to ensure an oxygen-limited environment is maintained throughout the carbonisation process.

Author contributions

M. E. Koulouri: conceptualisation, methodology, formal analysis, visualisation, writing – original draft; L. Owomuhangi: conceptualisation, writing – review & editing; Y. Lugali: conceptualisation; M. R. Templeton, G. D. Fowler: supervision, writing – review & editing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary information is available. See DOI: **https://doi.org/10.1039/D5EW00434A**.

The data supporting this article have been included as part of the SI. Further data can be provided upon request. Data collected from human participants are not available for confidentiality reasons.

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