Co-carbonisation of faecal sludge and biomass waste for resource recovery: Lessons learned from Uganda and Rwanda

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Keywords: faecal sludge, biomass waste, biochar, briquette, fertiliser
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Non-sewered toilets, such as pit latrines and septic tanks, are the most commonly used sanitation systems globally (WHO/UNICEF, 2023). The amount of faecal sludge (FS) generated from these facilities is expected to increase over the next decades, particularly in low- and middle-income countries, making the establishment of safe FS management solutions essential to maintain public health and environmental sustainability. The valorisation of human waste fits within the wider context of biomass waste management and is becoming increasingly timely when considered under the prism of a global energy crisis and food security challenges (Lohri et al., 2016). Pyrolysis (or "carbonisation" when aiming to maximise solid char production) is a technology that has gained a lot of interest for resource recovery from biomass waste, particularly for the production of biochar fertilisers and solid fuels (Krueger et al., 2020). In this context, FS can be considered alongside other biomass sources (e.g. woody and agricultural waste) as feedstocks for the production of soil amendments and solid fuel briquettes with lower environmental and financial footprints compared to commercial alternatives.

Research on FS co-carbonisation with biomass waste is gaining fast interest, however, the transfer of knowledge to real-world applications is currently constrained by the limited understanding of feedstock properties and their heterogeneity over time and across locations, as well as operational challenges in low-income settings. This study investigated the performance of two FS treatment plants (FSTP) in Kampala, Uganda and Nyamagabe, Rwanda that involve the co-carbonisation of FS with locally available biomass waste to produce FS-derived fertilisers and solid fuel briquettes. The specific aims were: a) to investigate the agricultural value of FS chars produced at the two locations for two consecutive years (2022-23); and b) to assess the effect of feedstock composition and operational conditions on the fuel quality of produced briquettes. Multiple samplings across locations over the course of two years allowed the statistical analysis of FS char characteristics for the first time.

Samples of briquettes and chars from biomass/FS materials were prepared by Water for People in Uganda and Rwanda, using a metallic air-locked drum kiln and a traditional brick kiln respectively. The process was initiated with available start-up fuels (wood, char or briquettes) and samples were left to slowly carbonise overnight. Due to limited temperature control, the highest heating temperature varied, typically between 300-400°C as estimated by thermogravimetric analysis of char samples. Produced char and briquette samples were sent to Imperial College London for characterisation. The samples were homogenised, ground and sieved (<500μm) before analysis. The calorific value was determined by bomb calorimetry using standard method ASTM D5865M-19. CHNS analysis was performed on a ThermoScientific Flash Smart Elemental Analyzer according to BS EN ISO 16948:2015. For the inorganic composition, samples were dry ashed at 490±5°C for 4 h and then digested with aqua regia for 2 h at 95°C, based on standard method US EPA 3050B. Nutrients (P, K, Ca, Mg) and trace elements were quantified by ICP-OES (Inductively Coupled Plasma Optimal Emission Spectroscopy) on an Avio 500 (Perkin Elmer, USA).

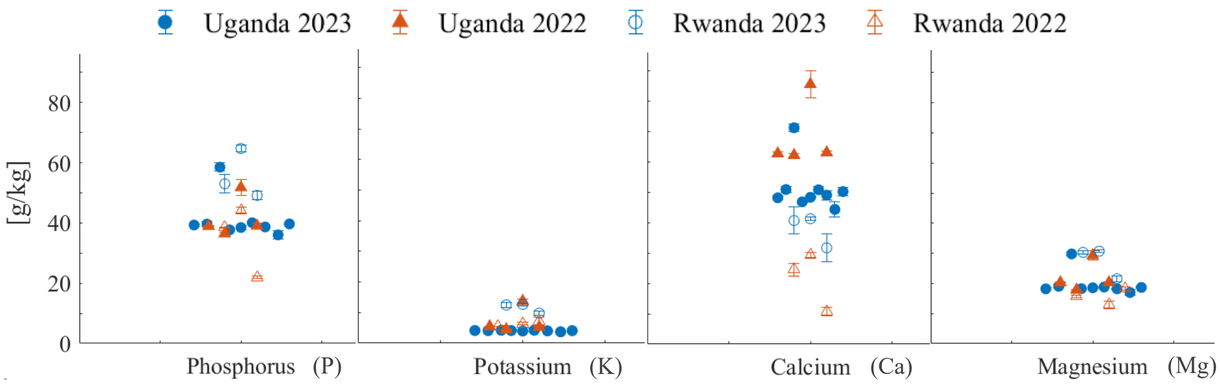

Figure 1: Nutrient content (P, K, Ca, Mg) of FS biochars produced in Kampala, Uganda and Nyamagabe, Rwanda during 2022 and 2023.

The FS chars had higher P content than animal manure fertilisers, showing promise for use in agriculture (**Figure 1**). The observed outlier values and variance with time and across locations highlighted the importance of comprehensive quality control testing at FSTPs. The K content was consistently low, while Ca showed the highest variability with time and location, which may be attributed to dietary factors or the type of containment facility (e.g. lined or unlined latrines) (Rose et al., 2015; Atwijukye et al., 2018). Quantifying the variability of FS char characteristics for different FSTPs is particularly helpful for sensitivity analyses of modelling applications on nutrient flows or life-cycle assessments that are usually based on generic databases. The parallel monitoring of heavy metal content is essential, and relevant data will be presented at the conference.

In terms of fuel quality, FS char showed poor fuel properties, mainly due to its high ash content, confirming the necessity of co-treatment with lignocellulosic biomass to increase energy content. The higher heating values (HHV) of chars derived from FS and various biomass sources are shown in **Table 1**. Sawdust (SD) and bagasse (BG) were found to be suitable locally available biomass sources in Uganda, with statistically comparable performance to commercial charcoal dust (CD). The HHV values and carbon content of char samples showed good correlation with their ash content, an easy and low-cost measurement that can be used to screen feedstock mixes and operational conditions on-site. While the HHV values for FS-containing briquettes were lower than the commercial norm (~22 MJ/kg), their slow burning properties and affordability make them an attractive alternative for communities that heavily rely on solid fuels, subject to ongoing optimisation.

Table 1: Higher heating value (HHV MJ/kg), carbon and ash content (%) of char and briquette samples from Uganda (2022). Briquette samples also contain binders which are added during extrusion (clay, molasses).

	Char samples				**Briquette samples**			
	FS	SD	BG	CD	FS:BG 50:50	FS:SD 40:60	FS:CD:SD 40:40:20	FS:CD 40:60
HHV [MJ/kg]	6.4 ±1.1	18.1 ±2.1	20.7 ±0.9	22.4 ±1.6	12.8 ±0.3	12.5 ±0.9	14.5 ±0.2	16.0 ±0.3
C [%]	17.4 ±0.5	53.3 ±2.4	55.3 ±2.1	58.5 ±0.9	33.7 ±1.9	31.3 ±2.1	39.4 ±1.4	47.6 ±1.1
Ash [%]	68.9 ±2.0	31.6 ±1.2	23.5 ±1.4	19.8 ±1.7	43.5 ±1.4	44.3 ±0.9	38.5 ±1.0	36.6 ±1.6

Overall, the findings brought to light the opportunities and limitations of FS resource recovery applications in developing countries. Site observations and carefully designed sampling protocols can shape research objectives of a fast-progressing scientific field. For example, the high ash content of FS char appears to be a limiting factor for its use as a fuel. Source interventions to limit ash content (e.g. urine diversion) and pre-treatment methods that avoid the introduction of sand (e.g. by replacing or improving current sand drying beds) should be investigated as suitable improvements, together with biomass waste co-treatment. Similarly, the direct communication of practical research outcomes to field applications can be a significant accelerator to achieve multiple SDGs around sanitation (SDG 6), clean energy (SDG 7) and food security (SDG 2). The soil improving properties of FS chars are promising and further nutrient enhancement methodologies can create pathways for the production of marketable fertilisers that can compete with or exceed the performance of commercial alternatives (Koulouri et al., 2024). Observations made on field and fundamental research findings are both essential for the establishment of safe and sustainable human excreta management practices in the developing world and beyond.

Acknowledgements

The authors would like to thank the Department of Civil and Environmental Engineering of Imperial College for the donation of a scholarship and the Society of Chemical Industry (SCI) for financially supporting this work. This project was also supported by the Royal Academy of Engineering under the Research Chairs and Senior Research Fellowships programme. The authors are grateful to Water for People staff for their support in facilitating this project, and Imperial College MSc/ MEng students Junqi Liang, Boyu Zhang, Nadia Angelica and Baiqi Lyu for contributing to analytical experiments as part of student projects.

References

Atwijukye O., Kulabako, R., Niwagaba, C., Sugden, S., 2018. Low cost faecal sludge dewatering and carbonisation for production of fuel briquettes. 41st WEDC International Conference, Kenya, 2018.

Koulouri, M.E., Templeton, M.R., Fowler, G.D., 2024. Enhancing the nitrogen and phosphorus content of faecal-derived biochar via adsorption and precipitation from human urine. J. Environ. Manage. 352, 119981.

Krueger, B.C., Fowler, G.D., Templeton, M.R., Moya, B., 2020. Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. Water Res. 169, 115253.

Lohri, C.R., Rajabu, H.M., Sweeney, D.J., Zurbrügg, C., 2016. Char fuel production in developing countries – A review of urban biowaste carbonization. Renew. Sustain. Energy Rev. 59, 1514–1530.

Rose, C., Parker, A., Jefferson, B., Cartmell, E., 2015. The Characterization of Faeces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. Crit. Rev. Environ. Sci. Technol. 45, 1827–1879.

WHO/UNICEF, 2023. Progress on household drinking-water, sanitation and hygiene 2000-2022.