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Faecal-wood biomass co-combustion and ash composition analysis

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HIGHLIGHTS

- Co-combustion analysis was investigated using a bench-scale combustor test rig.
- Raw human faeces (FC) contained 73.9 ± 4.4 wt% moisture as received basis.
- Blending with wood dust (WD) in a 50:50 ratio reduced moisture levels by ∼40%.
- Minimum acceptable blend for combustion without prior drying is 30:70 WD:FC.
- Fuel burn rates are 3.18–4.49 g/min for all the blends at air flow of 12–18 L/min.
- Oxygen, potassium and calcium are the most abundant elements in faecal ash.

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ABSTRACT

Fuel blending is a widely used approach in biomass combustion, particularly for feedstocks with low calorific value and high moisture content. In on-site sanitation technologies, fuel blending is proposed as a pre-treatment requirement to reduce moisture levels and improve the physiochemical properties of raw faeces prior to drying. This study investigates the co-combustion performance of wood dust: raw human faeces blends at varying air-to-fuel ratios in a bench-scale combustor test rig. It concludes with ash composition analyses and discusses their potential application and related problems. The study shows that a 50:50 wood dust (WD): raw human faeces (FC) can reduce moisture levels in raw human faeces by ∼40% prior to drying. The minimum acceptable blend for treating moist faeces without prior drying at a combustion air flow rate of 14–18 L/min is 30:70 WD: FC. For self-sustained ignition and flame propagation, the minimum combustion temperature required for conversion of the fuel to ash is ∼400 °C. The most abundant elements in faecal ash are potassium and calcium, while elements such as nickel, aluminium and iron are in trace quantities. This suggests the potential use of faecal ash as a soil conditioner, but increases the tendency for fly ash formation and sintering problems.

1. Introduction

The development of next-generation on-site sanitation facilities is underway in many parts of the world including the United Kingdom [1,2], Switzerland [3], and Canada [4]. Under the Reinvent the Toilet Challenge (RTTC), a Water, Sanitation & Hygiene program launched by the Bill and Melinda Gates Foundation, toilets are being designed to safely treat human excreta and recover useful by-products such as clean water, fertiliser and electricity. Toilets are required to operate in areas where there may be no water, energy or sewer connections. They must also be affordable: expected to cost no more than $0.05 per user per day [5]. These facilities are intended for the 40% of world's population that have no access to sanitation and including the 1 in 7 people that rely on unhygienic toilets, unsafely emptied pit latrines or open defecation, particularly where sanitation infrastructures are overburdened or not in existence.

The on-site sanitation facility 'Nano Membrane Toilet' (NMT) that is being developed at Cranfield University as part of the RTTC employs processes such as sedimentation and membrane filtration for removing and purifying the loosely bound water (mainly urine) in human excreta, and technologies such as the optimised archi-

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medes screw for transport of residual solids into an energy conversion unit, with subsequent thermochemical conversion of the solids into ash and heat energy [1]. Since raw human faeces contain as much as 77 ± 4 wt% moisture [6] and to limit the moisture entering the energy conversion unit, the residual solids are projected to undergo a pre-treatment process that involves partial drying and pelletisation. These processes can consume a significant part of the energy contained and recovered from the faecal material, if not adequately managed. More so, raw human faeces possess peculiar viscous, "sticky" characteristics, varying water-bound levels, and compositional non-uniformity from un-chewed and undigested foods that make sample homogeneity, handling and use difficult [6]. For instance, the "lumpy" food particles in the residual solids cause blockages and the sticky characteristics promote adherence to mechanical equipment [6,7], thereby making extrusion and pumping challenging. There is, therefore, a need to upgrade the physiochemical properties of the faecal matter, prior to drying and pelletisation, a process that can be improved by fuel blending.

Fuel blending is a process that combines two or more materials to produce a finished product with superior quality. It is a widely used approach in biomass combustion, particularly for feedstocks with high moisture, ash content (AC) or low calorific value [8]. Direct combustion of biomass and coal is progressively deployed in coal fired plants, particularly in Germany, and the Netherlands [9,10]. Agricultural waste, municipal solid waste and energy crops are also increasingly applied in boilers and power plants [11] at 10–25% blending ratio with fossil fuel or similar biomass material to reduce emissions and fossil fuel consumption or to utilise waste resources [12,13]. In developing countries, wood dust — also known as sawdust — is often used as bedding material and for clearing poultry waste in large quantities, and subsequently disposed of via open burning. Therefore, a fuel pre-treatment process that involves a blend with materials such as wood dust can make raw faeces more suitable for thermo-chemical conversion and for use in on-site sanitation technologies. This can enhance sustained fuel ignition and flame propagation, thereby improving process efficiency and the continuous use operation of the energy conversion unit. It can minimise the life-cycle energy requirement for drying and simplify the fuel pre-treatment processes. Overall, this can accelerate product development and diffusion with a link to existing user behaviour.

Co-combustion of two or more biomasses is a well-documented approach in the literature. Barber [10] showed that the addition of 4% dewatered sewage sludge cake and dried pellets was suitable for electricity generation in a 760 MW coal fired power station at a furnace temperature of 1200 °C and fuel feed rate of 240 t/h. There was no adverse effect on emissions and boiler operation, provided the overall moisture content (MC) of the feedstock did not exceed 14 wt% by weight. Stelmach and Wasielewski [14] investigated the co-combustion of sewage sludge with coal in a pulverised coal boiler and uphold the approach for sludge utilisation in Poland. Similar studies are presented for sewage sludge utilisation in circulating fluidized beds [15–17]. For thermogravimetric analyses, Jin et al. [18] showed that different blending ratios of dewatered sludge and coal had minimal influence on ignition temperature, flammability index, combustion characteristics index and emissions, provided the addition of dewatered sludge did not exceed 20 wt%. It was observed that NOx and SO_2 emissions reduced with increasing blending ratio, particularly at 30% dewatered sludge. Wang et al. [19] investigated the transformation of nitrogen in different blends of municipal sewage sludge (MSW) and cotton stalk, wheat and corn straw at a heating rate of 100 °C/min up to 900 °C and O_2 flow rate of 100 mL/min. They observed volatile nitrogen as the predominant form and reduced NOx emission, particularly for 30:70 MSW:corn straw blend. Peng et al. [20] showed that the process improved the char catalytic and alkali-metals melt-induced effect on the decomposition of textile dyeing sludge when the sludge was mixed and heated up to 900 °C at an air flow rate of 50 mL/min with 60 wt% microalgae sludge. Magdziarz and Wilk [21] showed that the co-combustion process favoured the treatment of sewage sludge at varying heating rate conditions, but ignition temperatures were affected by the different blend rates. These studies collectively identify the importance of blending ratios and influence on combustion and/or emission characteristics, but these are specific to the fuel stock.

Beyond energy recovery and emission reduction, fuel blending is being explored for nutrient recovery and utilisation and to understand nutrient transformation in residual ash samples. Li et al. [22] explored the co-combustion of MSW and wheat straw in a vertical tubular furnace reactor, in order to understand the transformation of potassium in ash samples. Yan et al. [23] utilised the method to inhibit the formation of polychlorinated dibenzo-p-dioxins and dibenzofluorans (PCDD/Fsfor) and observed the potential application for hospital waste. Folgueras et al. [24] studied sulphur retention in ash samples recovered from co-combustion of bituminous coal and sewage sludge. The sewage sludge was obtained from a waste treatment plant that utilised $FeCl_3$ for coagulation and it was observed that increased sewage addition improved sulphur retention due to the increased calcium oxide content in the sludge. Thus, the blending of the raw faeces with similar biomass material such as wood dust can find good application in on-site sanitation facilities, particularly in rural communities, where wood biomass is a readily available and utilised resource [25].

For faeces-specific studies, there is sparse information on the blending of human faeces with combustible materials for energy generation. Apart from Monhol and Martins [26] who investigated the co-current combustion of dried human faeces with polyethylene waste, other co-combustion studies including those of the authors [6,28,29] have primarily focused on the use of 100% human faecal matter or surrogate faecal material [30,31]. While the co-combustion of faeces with polyethylene waste [26] appears to be viable, the household application of such a fuel blending process can have severe environmental and health implications, due to the potential emissions of persistent organic pollutants such as polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs), polybrominated diphenyl ethers (PBDEs) and PCDD/Fs [27]. As such, a renewable energy source would be a more ideal blend material. Onabanjo et al. [6] showed that dry human faeces have a comparable energy content to wood biomass with similar combustion temperature profiles. Their study also showed that combustion can be applied to treat faecal matter with up to 60 wt% moisture, provided the combustor temperature is above 600 °C, but raised concern on the direct use of the material due to fuel-peculiar characteristics.

This paper therefore presents the co-combustion of raw faeces with wood dust in a bench-scale combustor test rig, as a means of demonstrating the application of fuel blending in the ongoing development of a novel on-site sanitation technology. Co-combustion experiments were conducted at various blend ratios and air flow rates to determine the minimum blend requirement and the optimum combustion operating conditions. Performance assessment was carried out on the basis of combustion temperature, fuel burn rate, modified combustion efficiency (MCE) and carbon conversion efficiency (η_{CCE}). The study concludes with an assessment of the mineral composition of the ash residues recovered from the co-combustion experiments and discusses their potential application and related problems.