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Evolution of faecal sludge chemical and physical characteristics during drying

S. Septien, S. W. Mirara, B. Makununika, A. Singh, J. Pocock,
K. Velkushanova & C. A. Buckley (South Africa)

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The effect of drying on faecal sludge chemical and physical properties for its reuse as agricultural product and biofuel was explored in this investigation. The nutrient content, calorific value and thermal properties were determined for faecal sludge samples dried at different moisture contents, in two different drying apparatus, one based on convective drying and the other on infrared drying. The results show that the nutrient content and calorific value were not affected during drying. On the contrary, drying modified the chemical form of nitrogen in the sludge, by binding it more tightly to the solid structure. Moreover, drying led to the increase of the thermal diffusivity, which improves its quality as biofuel by enhancing its ability to conduct heat. Faecal sludge, after being dried, could be used in agriculture as an organic fertilizer of slow nitrogen and phosphorous release, and as a biofuel with similar characteristics than wood.

Introduction

The urge to improve the critical sanitation situation suffered by approximately one third of the world population has led to the development of innovative technologies that are able to recover valuable resources from Human excreta. Different end-products can be obtained from faecal sludge, depending on the type of treatment process (Diener et al., 2014). One of the possible reuse applications of faecal sludge is in agriculture as fertilizer or soil-conditioner, which could be perceived as the most natural route to valorise the waste, as 60 to 70% of the nutrients from the fields are estimated to be found in human excreta (Malkki, 1999). Another possibility of reuse is as a biofuel, with heating values of 17 MJ/kg reported for faecal sludge from different African cities (Muspratt et al., 2014). These values are similar to biomasses such as coffee husks (16 MJ/kg), firewood (16 MJ/kg) and sawdust (20 MJ/kg). Faecal sludge is used as a biofuel in treatment plants, such as the Omniprocessor (Villarreal, 2015).

Drying is an important step in the treatment of faecal sludge for its safe reuse. This process enables to remove the moisture by the application of heat a deactivates the pathogenic organisms. The thermochemical conversion of sludge (namely combustion, smouldering, pyrolysis) requires the removal of moisture until a certain degree in order to avoid the failure of the process and, if possible, to achieve a positive energy balance for energy recovery. However, the effect of drying on the chemical and physical characteristics of faecal sludge has not been investigated enough in literature, whereas this has a considerable influence in the final reuse of the dried material. The present work aims at characterizing the evolution during drying of properties of faecal sludge deemed as the most important for its reuse in agriculture or as a biofuel. Indeed, the nutrient content, calorific value and thermal properties were measured for samples dried at different stages. Faecal sludge from pit latrines was selected as the feedstock for this study, as this type of sanitation facility is the most common in low-income countries, particularly in Africa (Cairncross et al., 2010; Habitat, 2008; Jain, 2011). Two methods of drying were employed in this study, namely convective and infrared drying. These types of drying technology can be found in large-scale faecal sludge treatment applications, e.g. the convective drier from the Pivot faecal sludge plant in Kigali, Rwanda (Miller et al., 2017) and the infrared dryer from the eThekwini municipality in Durban, South Africa (Harrison and Wilson, 2012).

Materials and methods

The sample in the present work was faecal sludge collected from ventilated improved pit latrines in the eThekwini municipality (Durban, South Africa). In the laboratory, the sludge was sieved using a 5 mm grid to remove detritus and trash. The sieved sludge was stored in a cold room at 4ºC, in order to prevent any biological degradation.

In the convective drying rig, faecal sludge is dried by the means of a dried air stream flow heated at different temperatures: 40, 60 and 80°C. The air stream flowrate was constant at 40 cm^3/s. The sample was placed in the drying zone as a flat thin layer of a few millimetres thickness or as 8 mm pellets.

The infrared dryer is a bench scale replicate of the full-scale infrared dryer located in Durban, LaDePa (Latrine Dehydration Pasteurisation), with a size reduction of approximately 10:1. During the experiments in the infrared dryer, the residence time and the infrared intensity were varied: 4 and 40 min for the residence time; 3.0, 4.7 and 6.0 kW for the power supply of the emitters (corresponding to temperatures of 85, 135 and 215ºC respectively, measured through a k-type thermocouple). An air flowrate of 10.4 m^3/min was induced in the drying zone through a suction system. The sample was introduced in the drier as 8 mm pellets produced by a hand-held extruder.

Different analyses were undertaken in the initial sludge and samples after drying in both drying apparatus, following the standard operating procedures from the Pollution Research Group (PRG, 2014). These include:

- Nutrient analysis: content of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) determined in a Microwave Plasma-Atomic Emission Spectrometer (MP-AES) model *Agilent 4100*; content of carbon (C) and nitrogen (N) measured in a CN analyser model *LECO TrueMac*; content of ammonium (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-) and phosphates (PO_4^{-3}) analysed using the spectroquant *Nova 60-Merck*.
- Physical analysis: calorific value measured in an oxygen bomb calorimeter model *Parr 6200*, using the same setup than Zuma et al. (2015); thermal conductivity, heat capacity and thermal diffusivity measured using a *C-Therm TCi* thermal analyser.
- Moisture content analysis, based on a Standard Method for the Examination of Water and Wastewater (APHA, 2012).

Each of the tests was repeated two or three times to verify repeatability. The uncertainty was determined from the standard deviation using a Student's t-distribution in a 90% confidence interval.

Results and discussions

Nutrient analysis

The nutrient content of the samples, shown in Figure 1 in dry basis, did not significantly vary as a function of the moisture content, the operating conditions and the drying method, therefore drying did not affect the sludge nutrient content. The mean values for the C, N, P, K, Mg and Ca concentrations were 368, 32, 85, 8, 12 and 30 g/kg dry solid respectively. Carbon was the major constituent, as expected for an organic material. The concentration of the nutrient elements were in the range of typical manure and compost nutrient content, expect for the phosphorus content that was higher (Cuevas, 1997; Ecochem, 2014; Ghaly and MacDonald, 2012). This result verified that dried faecal sludge has an interesting potential to be used as an organic fertilizer.

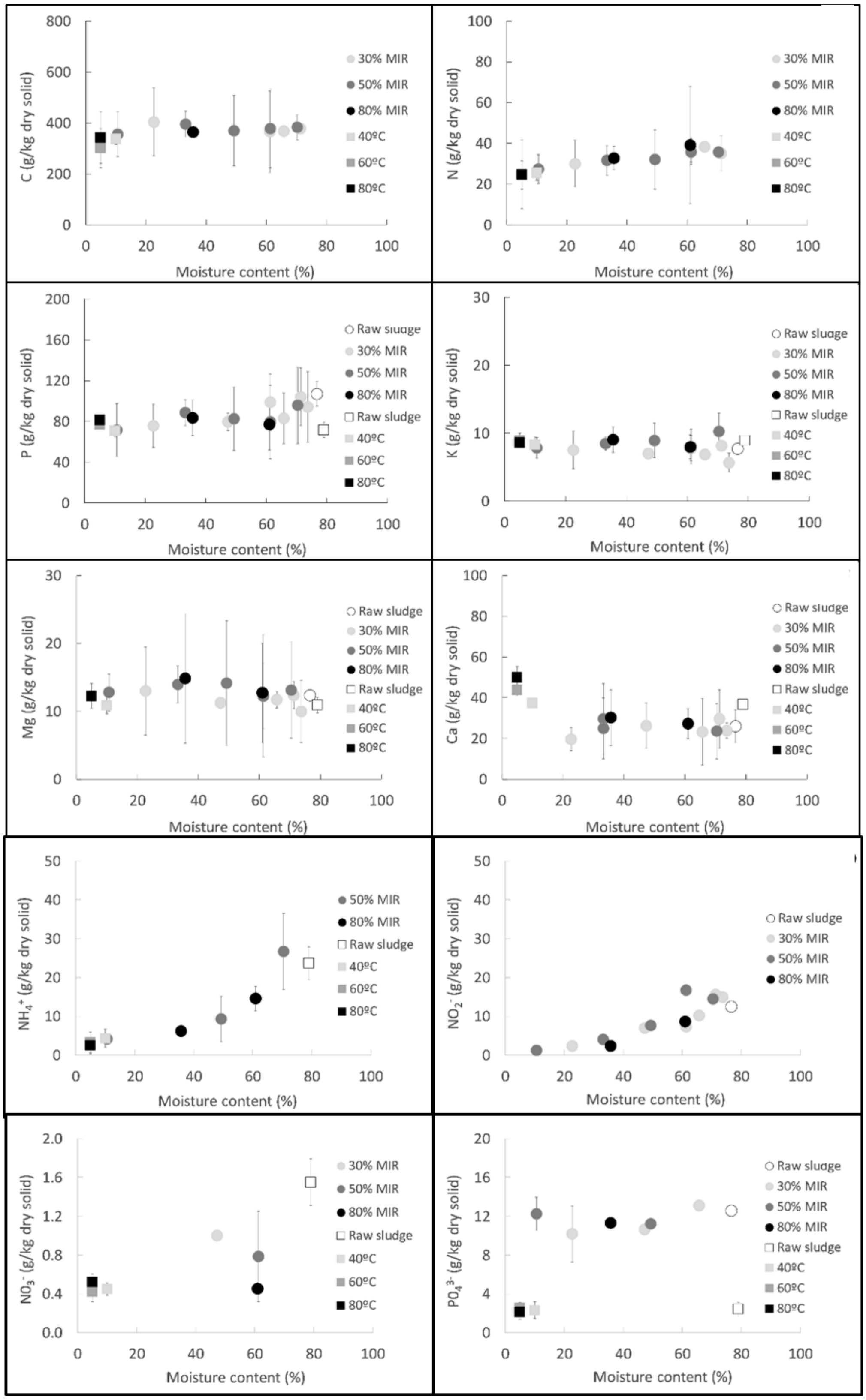

Figure 1. Nutrient analysis in the samples from the infrared drying rig (circle shape: raw sample, 30, 50 and 80% MIR) and convective drying rig (rectangular shape: raw sample, 40, 60 and 80°C)

Among the nitrogenous compounds, ammonium was the major compound, followed by nitrites and finally nitrates, as displayed in Figure 1. The sum of these concentrations was around 42 g/kg dry solid, equivalent to a nitrogen content of 25 g/kg dry solid, which is close to the measured total nitrogen content (32 g/kg dry solid). The concentration of these compounds dropped to 4 g/kg dry solid for the dried sludge, leading to a nitrogen content considerably lower than the total nitrogen. Considering that the total nitrogen content remained constant during drying, the decrease of the ammonium, nitrates and nitrites concentration during drying could be a result of chemical changes, in particular bonding of compounds with the dry bone structure. Therefore, if the dried sludge will be used for agricultural purposes, the nitrogen could be expected to be slowly released into the soil. This will be the opposite of fresh sludge for which the release of nitrogen could occur considerably faster, for example after irrigation or a rainfall.

The phosphate concentration remained constant during drying (2 g /kg dry solid for the samples from the convective dryer and 10 g/kg dry solid for the samples from the infrared dryer). The phosphorous content in the phosphates did not exceed 3 g/kg dry solid, which represents less than 4% of the total phosphorous content. This suggests that phosphorous was mainly founded bonded to the dry bone structure, and in much lower proportions as phosphate. It could be then expected that most of the phosphorus will be slowly released in the soil during the use of faecal sludge in agriculture.

Physical analysis

Figure 2 shows the physical properties measured for the samples dried in the convective and infrared drying rig at different operating conditions.

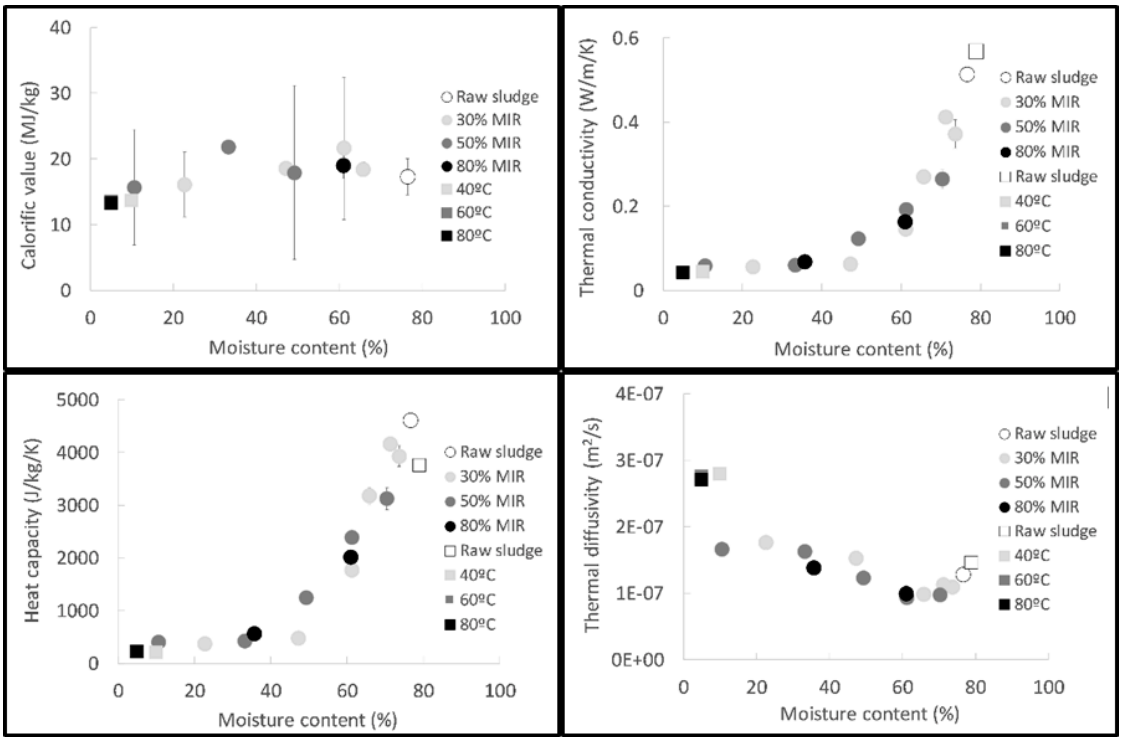

Figure 2. Physical analysis in the samples from the infrared drying rig (circle shape: raw sample, 30, 50 and 80% MIR) and convective drying rig (rectangular shape: raw sample, 40, 60 and 80°C)

The calorific value in dry basis was not significantly affected during either the infrared nor convective drying at the different conditions. The average value, 18 MJ/kg dry solid, is typical to that has been found in literature for faecal sludge and other biomasses resources. It is similar to the calorific value of some heating coals of low to medium rank, such as lignite, bituminous coal and peat (14 – 25 MJ/kg). Dried faecal sludge possesses then a suitable calorific value to be used as a biofuel.

The thermal conductivity and heat capacity drastically decreased during drying up to 40% moisture content, suggesting that the value of these parameters was controlled by moisture. The thermal conductivity and heat capacity of the initial faecal sludge were approximately the same than that of pure water, 0.58 W/m/K and 4187 J/kg/K. At moisture contents lower than 40%, these parameters attained a relatively constant value of 0.04 W/m/K and 400 J/kg/K, which are approximately ten times lower than that of the fresh faecal sludge. The same result with respect to the thermal conductivity was found during synthetic sludge drying from 80 to 30% moisture content (Xiangmei et al, 2014). This work reinforces the assumption that the thermal properties are mostly influenced by the moisture content, independently of the type of faecal material.

Drying led to the increase of the thermal diffusivity, defined as the ratio of the thermal conductivity to the product of density and heat capacity. The thermal diffusivity of the dried solid ($3\cdot10^{-7}$ m^2/s) was approximately 3 times higher than that of the raw sludge ($1\cdot10^{-7}$ m^2/s). Hence, the effect of the heat capacity and density decrease during drying should be more important than the effect of the thermal conductivity decrease. As the heating rate of a material is related to the thermal diffusivity, it can be expected that dried faecal sludge can be heated faster than the wet sludge, which makes the dried sludge a more suitable material for reuse as a biofuel. The thermal diffusivity of the dried faecal sludge is in the order of magnitude of common liquid and solid fuels.

Conclusion

Drying does not affect the nutrient content and the calorific value in faecal sludge, but it provokes some chemical and physical modifications: change of the nitrogen chemical form, probably due to binding to the dry bone structure; a decrease of thermal conductivity and heat capacity, leading to an increase of thermal diffusivity, which will be reflected by an increase of the ability of the sludge to be heated. The dried pellets has an interesting nutrient composition to be used as an organic agricultural product. If used as fertilizer, most of the nitrogen and phosphorous will be slowly released in the soil. The use of dried pellets as a biofuel is an interesting alternative, because of the relative high calorific value and good thermal diffusivity of the material, in the same range than diverse biomasses which are extensively used as biofuel (as wood).

This work presents the implications of drying on the reuse of faecal sludge. The data and knowledge generated in this study could be useful for the improvement of the faecal sludge management chain, particularly in regards to the reuse of dried faecal matter. Drying improves the qualities of faecal sludge as fertilizer and biofuel. The nutrient content and calorific value in dry basis are not affected by drying process, which means that, as faecal sludge is dried, the nutrients are concentrated and the gross calorific value increased (in wet basis). Besides, drying turns the nitrogen into a form which is more slowly released and improves the ability of faecal matter to conduct heat, leading to a better fertilizer and biofuel.

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Contact details

Dr. Santiago Septien Stringel from the Pollution Research Group (University of KwaZulu-Natal), researcher in the sustainable sanitation sector, has an expertise on rheology, drying and thermal treatment of Human excreta. Mr. Simon Mirara and Mr. Blessing Makununika are the master student that conducted the research from this project. Mrs. Anusha Singh from the Chemical Engineering department (University of KwaZulu-Natal) is specialized in heat and mass transfer phenomena, and process design. Dr. Jon Pocock from Chemical Engineering department (University of KwaZulu-Natal) is an specialist in processes related to the mine industry. Dr. Konstantina Velkushanova from the Pollution Research Group (University of KwaZulu-Natal) is a researcher specialized in the characterisation of faecal sludge. Pr. Christopher Buckley, Head from the Pollution Research Group (University of KwaZulu-Natal), has a long expertise in the wastewater and sanitation field.

Dr. Santiago Septien Stringel
Pollution Research Group
University of KwaZulu-Natal
4041 Durban
Tel: +27312601122
Email: septiens@ukzn.ac.za
www: http://prg.ukzn.ac.za/

Dr. Jon Pocock
Chemical Engineering
University of KwaZulu-Natal
4041 Durban
Tel: +312603377
Email: pocockj@ukzn.ac.za
www: http://chemeng.ukzn.ac.za