Final technical report

Project OPP1164143 – Characterization of faecal material behaviour during drying

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Partner institutions: Swansea University, Cranfield University

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Executive summary

Drying is a relevant unit operation during faecal sludge and fresh faeces treatment. It allows the removal of moisture from the faecal matter and its disinfection, so making it safer to handle, easier to transport and a more suitable biofuel. The Pollution Research Group (PRG), at the University of KwaZulu-Natal (UKZN), received a grant from the Bill & Melinda Gates Foundation through the OPP1164143 to investigate the drying of faecal materials (faecal sludge from onsite sanitation facilities and fresh faeces). The objectives of this research were to generate useful insight and data to overcome the current technological gaps from faecal wastes drying. This research project, done in collaboration with Swansea University and Cranfield University.

This research project was divided into three distinct phases: (i) a landscape study, (ii) experimental work, (iii) and dissemination of knowledge and data. The landscape study was conducted to identify the gaps in the drying technologies and the areas of greatest interest to explore through research. The experimental planning was based on the outcomes from the landscape study, and different kinds of experiments were carried in the three institutions. The next step was to disseminate the data and knowledge generated from this project, as well as data collected from previous projects and partner institutions.

The objectives from the experimental work included topics as: drying kinetics, heat of drying, boundedness of the moisture in the faecal material, thermal degradation, pathogens deactivation, physiochemical properties, morphological characteristics, boundedness of the moisture, odours. The experimental work from this project was carried out in three different geographical locations: PRG-UKZN, Cranfield University and Swansea University. The experiments were conducted using faecal sludge collected from on-site sanitation facilities from the eThekwini municipality (faecal sludge from ventilated pit latrines, urine-diverting dry toilets and an anaerobic baffled reactor from a decentralized water treatment system), as well as fresh Human faeces from donations at PRG-UKZN and Cranfield University. The faecal sludge samples from on-site sanitation facilities were exported to the United Kingdom (UK) for their testing at Cranfield University and Swansea University. The experimental work included the following analysis: thermogravimetry, thermal analysis, gas analysis, spectrophotometry, calorimetry, proximate composition analysis, CNS analysis, rheometry, dewatering, sorption isotherms, water activity analysis, thermal properties analysis, specific surface analysis, particle size distribution analysis, qualitative observations.

The outcomes from this research project highlight the importance of temperature on the drying kinetics and disinfection of the faecal matter. Moreover, the moisture boundedness at the different stages from the drying process was characterized and related to the variation of the faecal matter consistency, energy consumption, thermal properties and pathogens deactivation. Furthermore, the different types of faecal material were compared in terms of their drying and dewatering capabilities, and moisture boundedness. In addition to this, interesting results were obtained concerning the thermodynamic equilibrium of the process, properties of the dried solid, the suitability of radiative methods to dry faecal matter and the odour emission.

Overview of the project

Drying is a relevant unit operation during faecal waste treatment, including faecal sludge from on-site sanitation facilities and fresh faeces. It allows the removal of moisture from the faecal matter, so making it a more suitable biofuel and increasing the efficiency of combustion. The removal of moisture leads to a loss of weight and shrinkage of the faecal matter, which facilitates its handling and reduces the costs associated with transport. Drying also leads to the deactivation of pathogens, leading to a safer product that can be handled with reduced infection risks.

Drying is part of the innovative treatment sanitation systems developed under the program "Reinvent The Toilet Challenge" (e.g., reinvented toilets developed by Janicki Industries, Duke WASH-AID, Toronto University, Cranfield University, among others). Drying is also part of the faecal sludge treatment plants, such as the Omni-Processor and the process for biochar production from Biomass Controls. These units are based on the combustion or pyrolysis of the waste, so the control of drying is very important to achieve high efficiencies.

The TT5 transformative technologies portfolio meeting, held on the 25 to 29 July 2016 at the headquarters from the Bill and Melinda Gates Foundation (BMGF), was organized to identify the gaps that the grantees have been facing for the development and implementation of innovative sanitation technologies, and to find solutions for the way forward. One of the identified gap corresponded to faecal waste drying, which is a key process for the treatment of the faecal excreta but challenging to put into practice. Besides the inherent difficulties of the drying process, there is a lack of understanding and data related to its application to faecal waste, which limits the successful development and implementation of drying technologies in the sanitation sector.

The Pollution Research Group (PRG), at the University of KwaZulu-Natal, received a grant related to the TT5 portfolio meeting from the BMGF through the OPP1164143. The aim of this investment was to conduct an investigation about drying of faecal waster (faecal sludge from onsite sanitation facilities and fresh faeces), in order to generate useful insight and data to overcome the current technological gaps from the process. This research project, done in collaboration with Swansea University and Cranfield University, combined the expertise of these three institutions: (i) expertise in faecal waste characterization and drying at the PRG-UKZN; (ii) expertise in material science at Swansea University; (iii) and expertise in energy process systems at Cranfield University. Besides, Cranfield University has been involved in the development of a reinvented toilet, "the Nano Membrane Toilet", where the solid fraction of Human excreta is dried before combustion. Therefore, they could provide a practical perspective to the project from the challenges and lessons learnt from the development of the drying component from their toilet.

The transformative technologies (reinvented toilets and faecal sludge treatment plants) would benefit from the proposed investigation. Besides, the findings generated in this proposal will be useful to other practitioners involved in the desiccation of faecal sludge in drying beds or in the use of industrial dryers (example: LaDePa process, an infrared drier implemented in the eThekwini municipality, South Africa, to treat the sludge from pit latrines).

This research project was divided into three distinct phases: (i) a landscape study, (ii) experimental work, (iii) and dissemination of knowledge and data. The landscape study was conducted to identify the gaps in the drying technologies and the areas of greatest interest to explore through research. The experimental planning was based on the outcomes from the landscape study, and different kinds of experiments were carried in the three institutions. The next step was to disseminate the data and knowledge generated from this project, as well as data collected from previous projects and partner institutions. Important emphasis was brought in this aspect as the inefficient share of data is one of the main problems of the low availability of information in the literature about faecal sludge. The present report contains the findings and outcomes from the landscape and experimental work.

The landscape study was carried out to understand the state-of-the-art of faecal sludge drying, identify the relevant areas of investigation on this topic, and detect the specific gaps that sanitation practitioners are facing. The landscape study was conducted through a literature survey (papers, thesis, conference proceedings, reports, among others) and direct contact with sanitation practitioners (emails, discussions during conference and workshops, Skype calls, distribution of a form to select the areas of highest relevance to carry out research). The different institutions contacted in this phase of the project were as follow: Toronto University; Duke University; Montreal Polytechnique; Janicky Bioenergy; Pivot Works Ltd; Sanivation; Sanergy; Tide Technocrats; Biomass Controls; IHE-DELFT; SANDEC – EAWAG; Black Soldier Fly plant from BioCycle at eThekwini municipality; Bioresource Technology department at UKZN.

The objectives from the experimental work were set from the landscape study and included:

- Determination of the ideal temperature for drying and thermal degradation;
- Characterization of the effect of drying on the disinfection of the faecal waste (determination of the individual contribution of the heat input and moisture reduction effects);
- Characterization of the modifications of the physical properties of faecal material during drying (thermal properties, radiative properties, calorific value, specific surface, morphology);
- Identification and quantification of the boundedness of the moisture in the faecal matter;
- Evaluation of different methods to modify the boundedness of moisture in the faecal matter (i.e. viscous heating and aging);
- Estimation of the energy demand of the drying process;
- Analysis of the exhaust gas composition during drying.

The experimental work from this project was carried out in three different geographical locations: PRG-UKZN, Cranfield University and Swansea University. The experiments were conducted using faecal sludge collected from on-site sanitation facilities from the eThekwini municipality (faecal sludge from ventilated pit latrines, urine-diverting dry toilets and an anaerobic baffled reactor from a decentralized water treatment system), as well as fresh Human faeces from donations at PRG-UKZN and Cranfield University. The faecal sludge samples from on-site sanitation facilities were exported to the United Kingdom (UK) for their testing at Cranfield University and Swansea University.

The experimental work included the following analysis :

- Tests in an STA (Simultaneous Thermal Analyzer) coupled to FTIR (Fourier Transformation InfraRed) analyzer to determine the drying kinetics, thermal stability, heat of reaction and analysis of the exhaust gas (Swansea);
- Tests in a spectrophotometer to determine the radiative properties of faecal sludge (reflectance, transmittance) in the visible light and NIR radiation regions (Swansea);
- Tests in a TGA (ThermoGravimetric Analyzer) coupled to a GC-MS (Gas Chromatograph – Mass Spectrum) analyzer to determine the drying kinetics, thermal stability, and gas analysis (Cranfield);
- Tests in a TGA-DTA (ThermoGravimetric Analyzer – Differential Thermal Analyzer) to determine the drying kinetics, thermal stability, and heat of reaction (PRG-UKZN);
- Measurement of several properties of faecal samples dried in an oven at different temperatures and moisture contents (total solids content analysis, volatile solids content

analysis, water activity, thermal properties, calorific value, specific surface, qualitative observations) (PRG-UKZN);

- Centrifugation tests to determine the dewatering ability of the faecal samples (PRG-UKZN);
- Experiments using the saturated salts solutions method for the determination of the desorption and adsorption characteristics of the faecal material, measurement of the thermodynamic equilibrium moisture contents at given relative humidities (and water activities) and evaluation of the hygroscopic behaviour (PRG-UKZN);
- Measurement of several properties of the faecal material (CNS analysis, total solids content analysis, volatile solids content analysis, water activity, calorific value, rheology, particle size distribution, centrifugation, moisture analyzers), during different pre-treatments such as viscous heating (for sludge from pit latrines) and storage (for fresh faeces), in order to evaluate their effects on drying and dewatering (PRG-UKZN);
- Determination of the Ascaris eggs deactivation as a function of temperature and moisture content (PRG-UKZN).

The main outcomes from the experimental phase of this project consist in an important volume of data and knowledge for the sanitation community, as well as the development of methods that can be applied for the characterization of faecal sludge and fresh faeces drying, and assessment of drying systems. Besides this, the project led to a strong capacity building involving approximately 20 researchers and students. To finish, new research ideas and investigations were derived from this project, including MSc and PhD research projects.

Landscape study

Drying process

Drying is defined as the removal of water or any other solute from a moist solid. This process is a chemical engineering unit operation that is commonly applied in diverse applications in chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral and wood processing industries (Mujumdar, 2006).

Thermodynamics aspects

Drying is driven by the difference of thermodynamic activity between water as vapour in the air and water as moisture in the wet solid. Therefore, drying occurs when the thermodynamic activity of the moisture in the solid is higher than that of the vapour water in the air, and it stops at the thermodynamic equilibrium, i.e. when the water activities are equal. In the opposite, the solid can gain moisture if the activity of the vapour water in the air is higher than the activity of the moisture, for material defined as hygroscopic. In contrast, non-hygroscopic material cannot be rehydrated after losing its moisture.

The moisture content of a wet solid in thermodynamic equilibrium with the humidity of the surrounding air is termed as equilibrium moisture content. For a hygroscopic solid, the relationship between equilibrium moisture content and air humidity at a given temperature can be expressed by the sorption isotherm curves, which include a desorption (dehydration) and adsorption (rehydration) component, as shown in Figure 1. The pattern of the sorption isotherm curves depend on the temperature and surface properties of the solid. Note that the sorption isotherm presents a diaresis, which demonstrates that the way in which the solid is dehydrated and rehydrated differs.

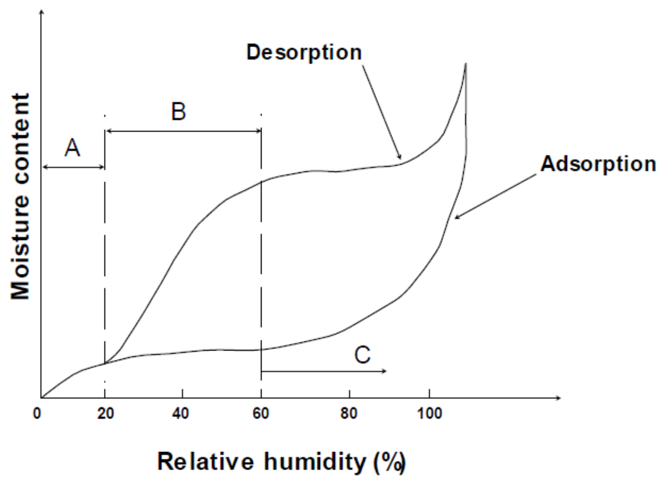

Figure 1. Sorption isotherms (Mujumdar and Devahastin, 2000)

As the equilibrium moisture content depends on the temperature and the relative humidity of the air, it is then very important to know its thermodynamic properties. An important tool for this is the psychometric chart (Figure 2), which shows the thermodynamic properties of an air-vapour mixture at constant pressure, often equated at sea level. The most relevant psychometric parameters for drying are:

- Absolute humidity, defined as the mass of water vapour per mass of dry air;
- Relative humidity (%), defined as the partial pressure of water vapour in air divided by the vapour pressure of water at a given temperature;
- Wet bulb temperature, corresponding to the liquid temperature attained when a large amounts of air-vapour mixture is put in contact with the surface;
- Dry bulb temperature, corresponding to the temperature of the air-vapour mixture.

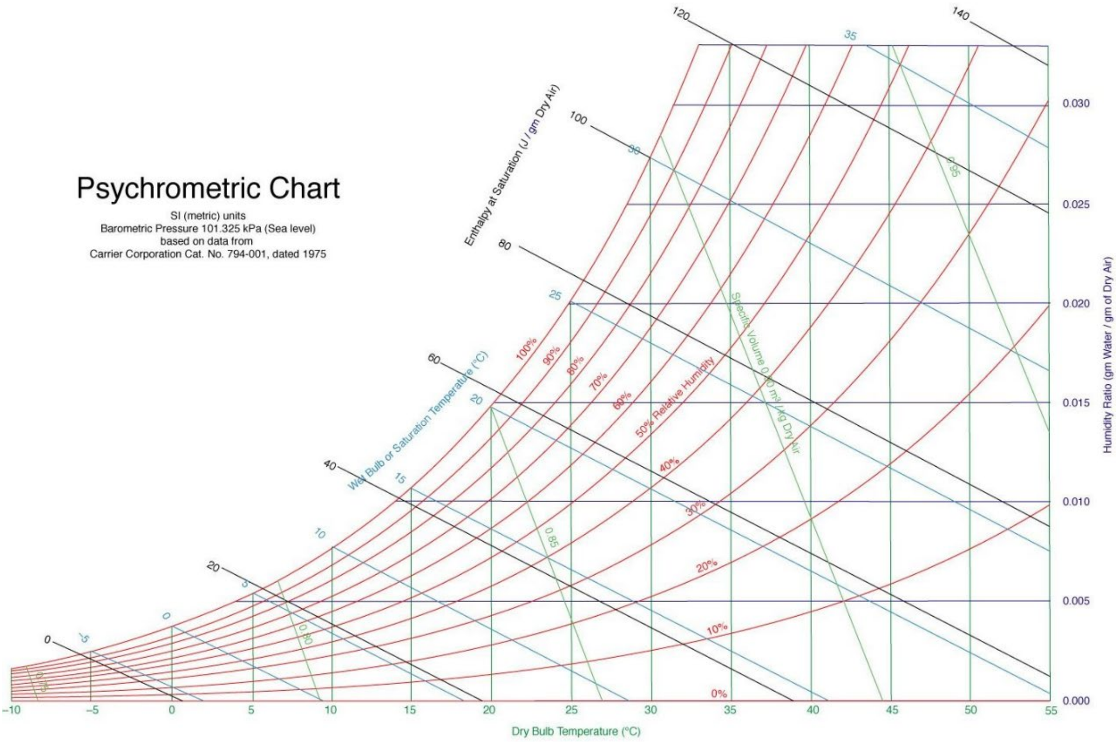

Figure 2. Psychometric chart of vapour water-air mixture (source: Carrier Corporation)

Air is saturated in humidity when its relative humidity is equal to 100%. The air loses then its ability to hold further vapour water and consequently drying cannot progress.

Types of moisture

The bounding of moisture with the solid matrix determines how drying will proceed. The two major types of moisture are:

- Bound moisture, which is linked to the solid matrix biologically, chemically or physically, and exerts a vapour pressure lower than that of water at the same temperature;
- Unbound moisture, which exerts an equilibrium vapour pressure equal to that of the pure liquid at the same temperature, so it behaves like water and can be removed relatively more easily in comparison to bound moisture.

Free moisture is defined as the amount of moisture in excess concerning the equilibrium moisture content at particular air temperature and humidity. It can be either bounded and/or unbounded.

The different types of moisture in a moist material are represented in Figure 3.

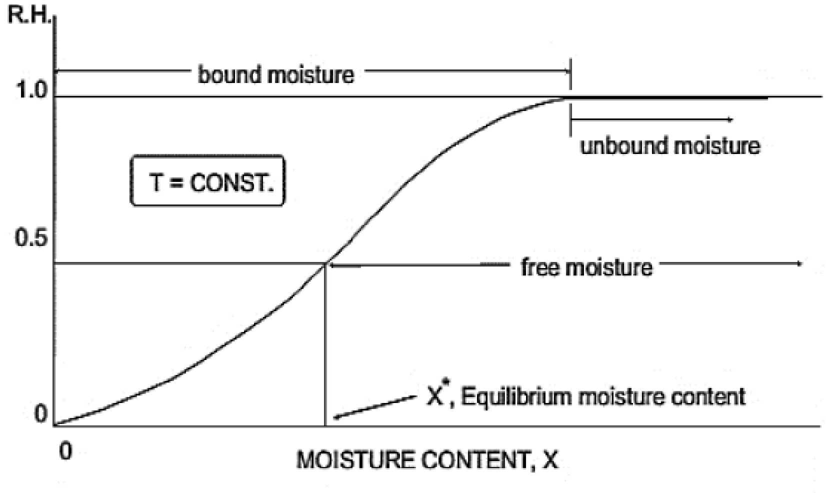

Figure 3. Different types of moisture (Mujumdar and Devahastin, 2000)

The sorption isotherm gives an indication on the binding mechanism of moisture in the moist material. In the example from Figure 1, the region A corresponds to moisture with tight bounds, whereas the moisture from region C is loosely held in the solid matrix. The region B is intermediary between A and C.

Drying mechanisms

Drying is a process that includes heat, mass and momentum transfer simultaneously. The heat provided during thermal drying increases the temperature of the material and supplies the latent heat for moisture vaporization. At the same time, the evaporated moisture is transferred from the solid to the surrounding air. The transfer of the moisture at the surface of the solid occurs through convection or molecular diffusion. The moisture migration from the interior towards the surface is done by different mechanisms, such as:

- Liquid diffusion if the moisture is in a liquid state;
- Vapour diffusion if the liquid has been evaporated within the solid;
- Capillary moisture movement, occurring due to capillary suction from the large capillaries to the small ones, driven by a capillary pressure gradient;
- Hydrostatic pressure difference, driven by the build-up of pressure within the solid after moisture evaporation.

Drying kinetics

The moisture content decrease during drying can be expressed by a curve from which the kinetics of the process can be studied, which is known as drying curve. In an ideal case, the drying curve is divided into three distinct stages: the constant rate period, the first falling rate period and the second falling rate period. Figure 4 represents a typical drying curve obtained under steady conditions.

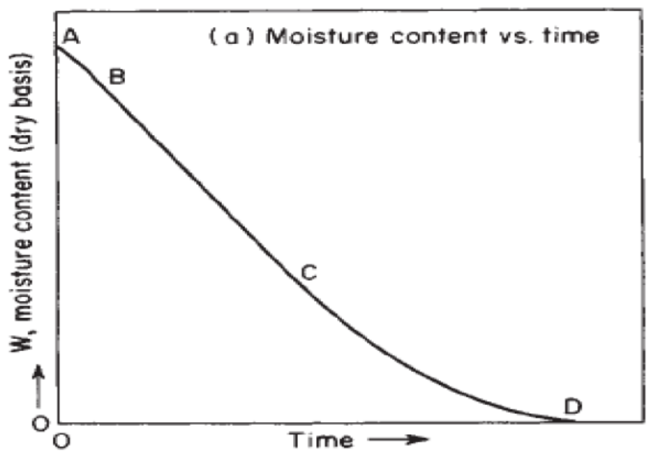

Figure 4. Typical drying curve (Moyers and Baldwin, 1997)

Preceded by the segment AB, representing a stage in transitory conditions, the segment BC corresponds to the constant rate period. In this stage, the entire surface of the material is saturated with moisture, which is replaced immediately after leaving the solid by moisture from inside the particle. Indeed, the internal and external mass transfer are in a dynamic equilibrium, and drying will proceed in a steady continuous manner. The temperature of the material during this stage is fairly constant, approximating the wet-bulb temperature value. A boundary layer of moisture is always available at the evaporating surface, and the heat provided to the solid is utilized for the evaporation of the water at the surface. Thus, the drying kinetics are controlled exclusively by external heat and mass transfer.

The point C corresponds to the critical moisture content, from where the drying rate starts to decrease. The portion CD is known as the falling rate period and is divided into two parts: the first falling rate period and the second falling rate period. During the first falling period, the surface of the wet solid cannot be anymore maintained saturated in moisture. In fact, the moisture at the surface evaporates at a faster rate than it can be replaced from inside the particle. The temperature of the material will start to increase from the wet-bulb temperature to the final temperature. During this stage, the drying rate is influenced by both internal and external transfer. In the second falling rate period, it can be considered that the surface is completely dry and an evaporation front progress towards the centre of the solid. The kinetics from this stage is dependent only on the moisture internal mass transfer.

Note that in a real case, the drying curve can deviate from the ideal case and does not necessarily present all the kinetic stages described above.

Factors affecting drying

The rate at which drying occurs depends on the power supplied by the heating source, type of moisture and the conditions influencing the transfer rates, such as the characteristics of the solid (geometry, size, porosity) and the external conditions (air temperature, velocity and humidity).

As drying progresses, the removal of moisture leads to the chemical and mechanical re-arrangement of the dry bone of the solid. The changes undergone by the solid during drying can influence the internal transport of the moisture and then affect the drying rate.

Temperature plays an important role in the quality of the product. Some products are temperature sensitive as their biological, chemical and/or physical properties can change if a limit of temperature is exceeded. For this type of product, drying should not be conducted at a temperature higher than that from which its quality is compromised.

Drying technologies

Drying technologies are classified according to the method of how heat is supplied to the wet material and how the evaporated moisture is evaporated. Dryers that expose the solid to a hot gas stream are known as direct or adiabatic. Dryers heated by conduction or radiation are called indirect or adiabatic. The most conventional drying technologies categories are as following:

- Convective hot air dryers (direct dryer) where heat is supplied by convection from a hot air stream and the evaporated moisture is taken away in the air stream. This drying method is by far the most common in spite of the relatively low thermal efficiency, which is due to the lack of a cost-effective method to recover the latent heat of vaporization from the exhaust. This type of drying requires the handling of large volumes of gas, so usually, convective drying plants presents a large footprint and gas cleaning constraints.
- Contact dryers (indirect dryer) where heat is supplied by contact with a hot wall, and so conduction is the main heat transfer driving force. Moisture is evacuated from the drying chamber by a vacuum or a moderate gas flow, in order to avoid humidity saturation of the air which can stop drying.
- Radiative dryers (indirect dryer) where heat is supplied by infrared radiation, microwave or radio dielectric frequency. Infrared radiation has relatively low penetration within the materials and then heats mostly the surface of the wet solid. In contrast, microwave and radio dielectric frequency waves can penetrate deep within the solid. So the heating of the material is done at the bulk volume without the need for conduction. Gentle convection or vacuum are usually applied for the removal of the evaporated moisture. Microwave drying has limited applications up to date, due to high capital and operating costs. In contrast, infrared drying has found important applications in niche markets, such as the drying of coatings and paintings, and radiofrequency in the drying of thick lumber and coated papers (Mujumdar, 2000).
- Solar dyers where the heat is provided from solar energy (more details in the next section).

It is possible to combine the heat transfer modes in the dryers, e.g. conduction or radiation with convection, to gain in thermal efficiency. Alternative methods to thermal drying also exists in the industry, as for example freeze drying, where the moisture is sublimed at low pressure after previously freezing the solid. This method is not commonly employed in the industry because of its high costs, except for highly heat-sensitive materials, such as some biotechnological, pharmaceutical or food material with high flavour content.

Among each drying method, several technologies have been developed, and the innovations carry on. Among the innovation with a promising future, we can find:

- Convective drying using superheated steam which has shown to yield higher efficiency and often higher product quality (Mujumdar, 2000);

- Fry-drying where the wet material is immersed in hot oil with temperatures above the water boiling point;
- Use of acoustic waves or vibrations during drying to increase the heat and mass transfer rate, and at the same time to promote solid-liquid separation;
- Use of explosion puffing where the wet solid is heated until reaching a certain pressure, followed by a sudden decompression that leads to an explosion due to the brutal moisture evaporation, which increases the porous network;
- Foam-mat drying where a liquid is turned into a porous foam for faster drying.

Peculiarities of faecal sludge drying

NOTE: The present literature review focuses mainly on faecal sludge from on-site sanitation facilities, but the present information could be applied to fresh human faeces.

Reasons for drying

Drying is an important step for the treatment and disposal of faecal sludge. The primary goal of drying is to eliminate or reduce the biohazard characteristic of the sludge, by killing the pathogenic organisms present on it by the effect of moisture reduction and high temperatures. As it can be seen in Table 1, most bacteria cannot develop below a water activity of 0.91, including pathogens such as Escherichia Coli, Salmonella, Shigella and Vibrio Cholerae. This result implies that most of the pathogenic bacteria can be deactivated during drying if the sludge achieves a moisture content corresponding to a water activity lower than 0.91. Figure 5 shows how the deactivation time of common pathogens considerably decreases by increasing the temperature. The "safety zone", where all the pathogens will be deactivated, can be achieved at 70ºC in a few minutes. The time to achieve the "safety zone" could be reduced to seconds by increasing the temperature above 70ºC, according to the extrapolation of the trends observed in Figure 5.

Moreover, the mass and volume of sludge are reduced during drying, leading to lower handling, transportation and storage costs. Besides, the moisture reduction during drying leads to the increase of the calorific value, consequently turning the sludge into a suitable biofuel. Drying enables to attenuate the fetid odours from sludge, lowering the discomfort levels from this material.

Table 1. Minimum water activity for microbial and spore development (Mujumdar and Devahastin, 2000)

Pathogen	Water activity
Pseudomonas, Bacillus cereus spores	0.97
B. subtilis, C. botulinum spores	0.95
C. botulinum, Salmonella	0.93
Most bacteria	0.91
Most yeast	0.88
Aspergillus niger	0.85
Most molds	0.80
Halophilic bacteria	0.75
Xerophilic fungi	0.65
Osmophilic yeast	0.62

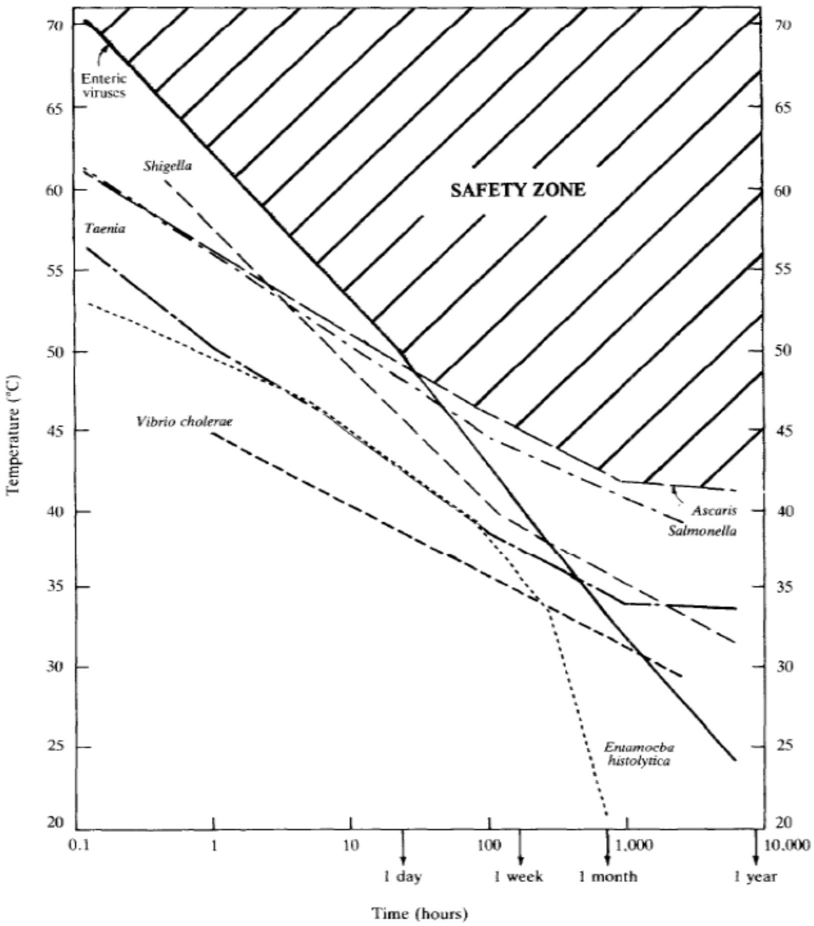

Figure 5. Temperature – time relation for the disinfection of pathogens (Feachem et al., 1983)

Moisture in sludge

In order to better understand faecal sludge drying, it is important to know how moisture is present in the material. Faecal sludge can be considered as a slurry with colloidal material, particles and polymers forming a network where moisture is integrated into different ways. Figure 6 depicts the distribution of moisture in a typical sludge into different types.

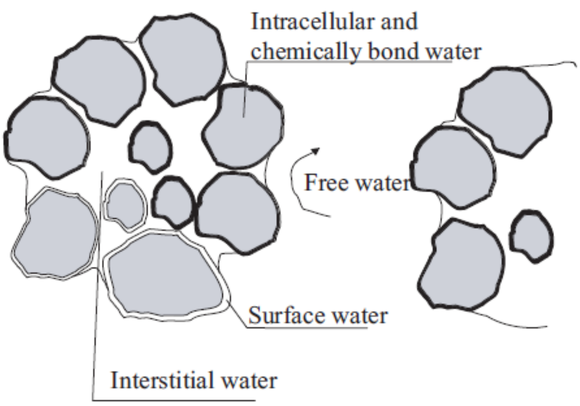

Figure 6. Water distribution in the sludge (Chen et al., 2002)

The free moisture is not attached to the sludge particles, and it is subordinated to gravity force so that it can be removed from the sludge by gravity-based processes such as settling. The interstitial moisture is found trapped within clusters of sludge flocs and capillaries, and can be removed by strong mechanical forces. Surface moisture or vicinal moisture (Mowla et al., 2013) is physically bonded to the surface of the flocs by adsorption and adhesive forces, and can hardly be removed mechanically. Chemically bonded moisture or hydration moisture (Mowla et al., 2013), is attached to the solid by chemical interaction, and its removal requires thermal drying. Intracellular moisture is contained inside the cells and can be removed only by breaking the cell wall structure, which can be done by heating, freezing or electro-induced forces.

In general terms, the moisture that can be removed by dewatering means is termed as "free moisture" (different term than the truly free moisture described above), which contrast with the term of "bound moisture" designating the moisture that can only be removed by thermal drying. Free moisture includes then the truly free moisture, interstitial moisture and a partial part of the surface moisture. Bound moisture encompasses the chemically bound water, the intracellular water and a partial part of the surface moisture. Note that the limit between free and bound moisture content, according to the previous definitions, can change following the involved dewatering methods. For example, the addition of polymers can break some chemical or physical bonds so that chemically bonded moisture or surface moisture can be partially removed by mechanical dewatering.

Physical changes of faecal sludge during drying

The removal of moisture content from the sludge induces mechanical stresses and a re-arrangement of the dry bone structure, which is reflected by perceivable physical changes. These have to be taken into consideration for a full comprehension of dying. Nevertheless, in the best of our knowledge, no such investigations have been carried for faecal sludge, on the contrary of sewage sludge where extensive investigations exist. According to these studies, the major changes undergone by sludge during drying are summarized as follow:

- Change of phase from a liquid to solid-state, which has important implications on the sludge rheological properties and then on the convey of sludge in the drier. During this transformation, the sludge passes through the intermediary stage of plastic and sticky behaviour. Stickiness can cause fouling in the drier and consequently a drop in its performance (Kudra, 2003), particularly in the case of contact dryers. The different phases during drying are illustrated in Figure 7.
- Shrinkage of the sludge, which can lead to a reduction in volume between 50 to 70% and occurs mainly during the constant rate period (Léonard et al., 2004, 2003a, 2003b, 2002; Tao et al., 2005).
- Formation of crust or skin at the surface (Tao et al., 2006), which can constitute a barrier for mass and heat transfer, and is more likely to occur in cases of fast drying ;
- Cracking of the surface, which occurs mainly in the falling rate period, and can occupy 30 to more than 50% of the volume (Léonard et al., 2004, 2003a, 2003b, 2002; Tao et al., 2005). Cracking can enhance the diffusion of evaporated moisture out of the particle, increasing the drying rate.

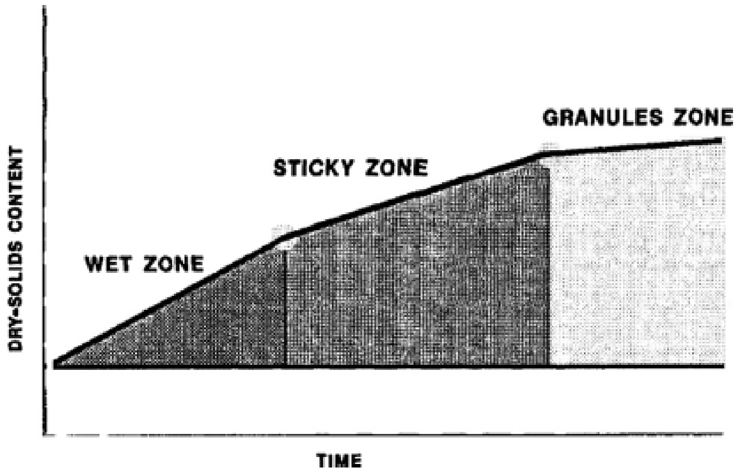

Figure 7. Presentation of the different phases during conductive drying (Lowe, 1995)

Technologies for faecal sludge and faeces drying

In the faecal sludge field, drying is typically performed in drying beds. However, this practice is unable to lead to low moisture content and the drying times are usually long. With the emergence of new technologies in the last decade, thermal drying has gained a relevant place.

Drying is an expensive process as moisture evaporation is energy-intensive due to the high water vaporization latent heat. In order to reduce the energy consumption, a dewatering step should precede drying in the case of a material with high moisture content. It is important to improve the existing dewatering technologies, to increase the amount of moisture that can be dewatered, which will reduce the need for thermal drying.

Table 2 shows some of the faecal sludge and faeces drying technologies that are currently available or being developed. It can be seen that most of these technologies rely on convective and contact drying, with only a few based on infrared, microwave and solar drying. The possibility to use an alternative type of drying, such as superheated steam drying and fry-drying, have not been explored by the moment, even if they have shown a great potential for sewage sludge (Bennamoun et al., 2013).

As a relatively recent technology in the on-site sanitation sector, drying presents considerably wide areas of exploration to carry on. Lessons and good practices can be obtained from the experience in other sectors where drying is in a more mature stage, particularly for similar material as sewage sludge. Nonetheless, drying technologies have to be specific to the faecal waste characteristics and context. In particular, the technologies must be as cost-effective as possible, due to the low budget available for faecal sludge management in developing countries, which makes difficult the implementation of high-tech equipment requiring a high investment.

An interesting option would be the development of in-situ drying systems where the faecal material will be dried at the proximity of the generation point. This aspect would lead to a significant reduction in the transportation costs, as considerable less water will be transported with the sludge to the treatment plant.

The source of energy employed for drying is an important parameter. As seen in Table 2, heat from combustion can be recovered for drying when the faecal waste is used as a fuel. However, when the faecal material is not combusted, an external source of energy has to be employed. This fact implies the necessity to supply continuous energy to the drying process, as electricity or fuel, to maintain it.

Solar thermal energy could be then a suitable solution to bring free energy to the process, leading to a decrease in operating costs. It could also be used as an extra source of energy in the combustion process, in order to guarantee enough low moisture content of the solid and lead to a heat recovery with higher efficiency.

A faecal waste drying flow diagram is proposed in Figure 8.

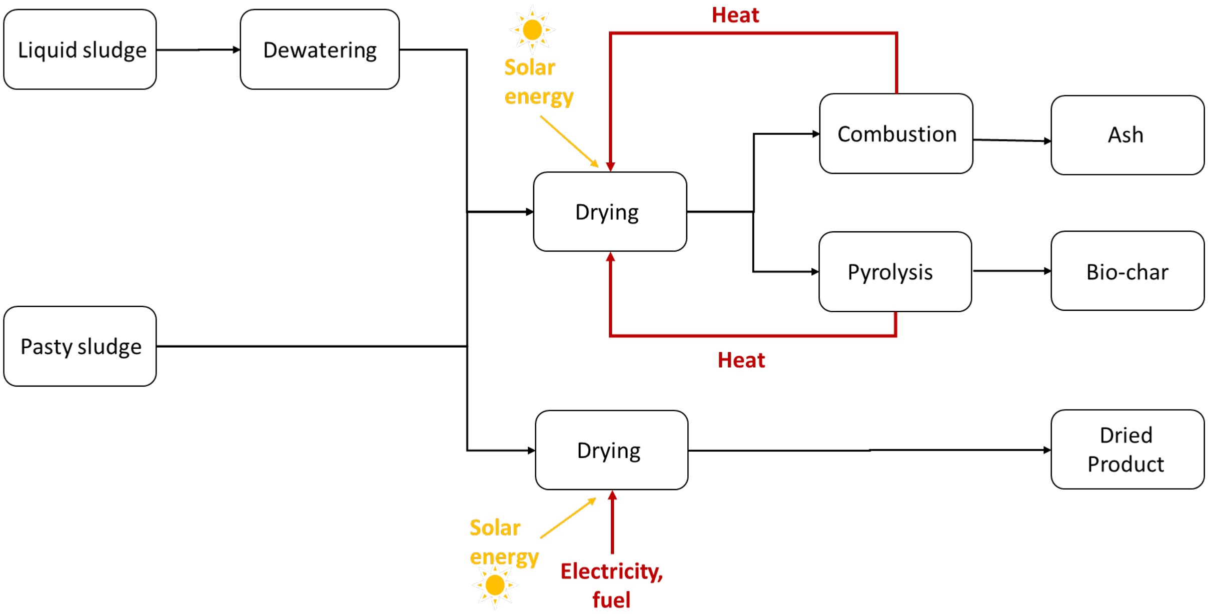

Figure 8. Faecal waste drying flow diagram

Table 2. List of faecal sludge and faeces drying technologies

Type of drying	Technology	Application	Place in the process	Energy source	Source
Convective drying	Belt dryer	Faecal sludge treatment plant from Tide Technocrats	Drying before a pyrolysis unit for biochar production	Heat from the combustion of the pyrolysis fumes	(Tide-Technocrats, 2016)
	Vertical multi-tray dryer	Reinvented "Firelight" Toilet from Janicki Industries	Drying before a combustion system	Heat from faecal sludge combustion	(SuSana, 2015)
	Rotary dryer	Faecal sludge treatment plant from Pivot	Final treatment (reuse of the product as biofuel)	Combustion of paperboards	(Pivot, 2016)
Contact drying	Hot surface wall screw conveyer	Faecal sludge treatment plant, "Omniprocessor", operated from Janicki Industries	Drying before a combustion system	Heat from faecal sludge combustion	(Villarreal, 2015)
	Heated rotary plate	Reinvented "A Better Toilet" from Research Triangle Institute	Drying before a combustion system	Heat from faecal sludge combustion	(RTI, 2013)
Convective, contact, radiative drying	Drying in the top of a fixed bed with a smouldering front at the bottom	Reinvented "Sanitation NoW" from Toronto University	Drying before a smouldering system	Heat from faecal sludge smouldering	(Yermán, 2016)
Convective and radiative	LaDePa machine (convective pre-drying stage, followed by an infrared belt dryer stage)	Treatment of faecal sludge from VIP latrines in eThekwini municipality	Final treatment (reuse of the product in agriculture)	Diesel generator providing the hot air and electricity	(Harrison and Wilson, 2012; Mirara, 2017)
Radiative	Microwave dryer	Treatment of faecal sludge in emergency cases	Final treatment	Microwave radiation generated using electricity	(Mawioo et al., 2017)
Solar	Greenhouse dryer	Faecal sludge treatment plant from Pivot	Pre-drying before the rotary dryer (see above)	Solar energy	(Pivot, 2016)

Technological gaps

During the development and operation of faecal sludge and faeces dryers, the sanitation practitioners have faced several challenges and technological gaps that need to be overcome. The following list shows some of the major technological gaps that have been identified (non-exhaustive list).

Thermal degradation of the dry-bone during drying

During thermal drying, the heat provided for moisture evaporation can induce a thermal degradation of the material. The thermal degradation can cause modifications of the dry-bone structure of the faecal matter and a loss of material through volatilization, which can have an impact on the quality of the dried product for its reuse. For example, it can lead to a decrease of calorific value or the nutrient content of the dry-bone. It is therefore important to characterize the conditions on which the material is thermally degraded and its consequence on the properties of the material.

Odour emission

Faecal material drying can enhance the release of volatile organic compounds into the environment, which are the main responsible for the unpleasant odours of faecal matter. The emission of odours can create olfactory nuisances for the people at the surrounding of the drying unit and constraints for the implementation of a drying process (example: need to comply with regulations in regards to odour emission).

The volatilization of compounds during drying should be then characterized, for example, by identifying the type of molecules released during the process and quantifying their amounts as a function of the operating conditions. The characterization of the odour emission of the process will enable to set odour management strategies, such as the selection of suitable exhaust gas post-treatment technologies, the selection of the operating conditions to minimize odour emission, the most appropriate location of the plant, among other points.

Crust formation

The crust formation can constitute a barrier for drying of the core of the faecal material, by limiting the mass transfer of the moisture to the environment. It can have negative consequences in the performance of the process, such as a material non-uniformly dried with the core of the material remaining wet and, consequently, a favourable environment for pathogens development. Therefore, crust formation can also limit the pasteurization of the faecal waste during drying. Crust formation should be thus well understood to find methods to mitigate it.

Change of consistency

The change of consistency during drying from a liquid slurry to granular solid can have important implications in the process. Indeed, the rheological, viscoplastic and viscoelastic properties of the material are modified by the removal of moisture, which has to be taking into account for the design of the dryer. For example, the conveying system should consider that the sludge will be fed into the drier as a slurry, and it will exit as a granular solid.

Stickiness

During the sticky phase, the faecal material can pose problems of clogging and fouling. The stickiness requires then to be characterised to have a better insight into this phenomenon, which will allow finding solutions to limit its occurrence and effects.

Evolution of the physical properties of faecal matter during drying

The removal of moisture during drying usually leads to changes in the physical properties of the material, such as shrinkage, density reduction, the variation of the thermal and radiative properties, among others. In other words, drying is a dynamic process with the properties of the material varying along with it. The evolution of the physical properties must be known for the correct design and sizing of the equipment.

Identification of the types of moisture

The moisture in the faecal sludge and faeces can be broadly categorized into two different terms: bounded and unbounded. The determination of the distribution of moisture can provide valuable information about the dewatering and drying requirements. For example, if the faecal material presents high amounts of unbounded moisture, it could be supposed to have a high potential for dewatering. In the opposite, dewatering will be limited or null for materials with high amounts of bound moisture.

Likewise, the distribution of the different types of moisture has an impact on the energy balance. Indeed, the evaporation of unbounded moisture demands a similar latent heat than pure water, while the energy demand will be higher for bound moisture that requires an extra energy input to break the physical, chemical and biological bounds. Therefore, the latent heat of pure water would be used in the energy balance for faecal materials with high unbound water content. In contrast, the heat of moisture evaporation should be ideally measured when the moisture is mainly bonded.

Pasteurization performance of the process

One of the main targets od frying is the pasteurization of the faecal waste. Therefore, it is of high importance to determine accurately which conditions all pathogens destroyed. There is some available information on literature; however, a consensus is missing up to now.

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Experimental work

Feedstock

The experiments were conducted using 4 types of faecal material:

- Faecal sludge from the anaerobic baffled reactor (ABR) from a decentralized wastewater treatment (DEWAT) plant;
- Faecal sludge from urine diversion dry toilets (UDDT);
- Faecal sludge from ventilated improved pit (VIP) latrine;
- Fresh faeces collected from anonymous and voluntary donations.

The faecal sludge samples were sampled during pit emptying campaigns within the eThekwini municipality (Durban metropolis), in South Africa. The ABR was collected during pit emptying from a vacuum truck, as the samples were quite liquid (~ 90%wt moisture content). In the case of the UDDT faecal sludge, the collection of samples was done during manual pit emptying (i.e. using spades, forks and bins), as the sludge was semi-solid (~ 75%wt moisture content). The VIP sludge came from two different sources. In the first case, water was added into the pit for its liquefaction in order to enable the pit emptying using a vacuum truck. This VIP faecal sludge had a liquid consistency with an average moisture content of 95%. In the second case, the VIP sludge was collected during manual pit emptying, therefore it was much drier than the former one. It had the same semi-solid consistency than the UDDT sludge, with a moisture content of approximately 75%wt. To distinguish the two VIP sludge samples in this report, the drier one will be referred to as "dry VIP", where the wetter one as "wet VIP".

The fresh faeces donations were done at the University of KwaZulu-Natal (UKZN), South Africa, and Cranfield University, United Kingdom (UK). The Ethics Committee from both institutions granted permission to collect and use faecal material (ethical clearance reference EXM005/18 at the UKZN and CURES/2310/2017 at Cranfield University). The moisture content of the collected faeces at Cranfield University, versus 80% at UKZN.

The faecal sludge samples from on-site sanitation facilities were exported to the United Kingdom (UK) for their testing at Cranfield University and Swansea University. The courier of the samples required a Material Transfer Agreement (MTA) and Export Permit from the Health Department of the Republic of South Africa (reference J1/2/4/2). The export process was done between UKZN-PRG and Cranfield University. For the laboratory work performed at Swansea University, the samples to analyze were prepared at the facilities of Cranfield University and then transported in sealed containers to Swansea.

The ABR, UDDT and VIP samples are differentiated from the faeces in this report. The former ones are designated as “faecal sludge”, whereas the latter as “fresh faeces”.

Kinetics

Motivation

The drying kinetics allow determining how fast faecal sludge dries, which is essential information for the design, operation, and optimization of driers.

As the temperature is one of the most influencing parameters during drying, the kinetics were determined in a wide range.

Experimental procedure

Drying experiments were performed in a thermogravimetric analyzer (TGA) at UKZN, Cranfield University and Swansea University. The thermogravimetry analyzer is a device where the mass of the sample is constantly measured at a set temperature. During these tests, the drying chamber was heated at a given heating rate until reaching the set temperature from where it stabilized. A carrier gas stream flowed through the measurement chamber in order to heat the sample by convection and remove the evaporated moisture. The moisture content of the sample was measured through the loss of mass of the sample during the transformation, assuming that the loss of mass was exclusively due to the moisture evaporation. The operating conditions are summarized in Table 3.

Table 3. Experimental conditions during the TGA experiments at UKZN, Swansea University and Cranfield University

	UKZN	**Swansea**	**Cranfield**
Model of the instrument	*SHIMADU DTG-60A*	*Perkin Elmer STA 6000*	*PerkinElmer TGA 8000*
Heating rate (°C/min)	50	10	100
Set temperature (°C)	50, 100, 150 and 200	55, 85, 105, 155 and 205	55, 85, 105, 155 and 205
Carrier gas flowrate (ml/min)	50	30	4
Mass of sample (mg)	70	40	40

Experiments were also performed in a moisture analyzer *Radwag Max 50* at UKZN. The principle of operation is similar to the TGA as described above: the sample mass is measured as it is heated, here through an infrared emitter. The experiments in the moisture analyzer were carried out at 105°C with 1.5 g of sample spread in an aluminium crucible of 90 mm diameter.

Results

Results obtained in the TGA at UKZN

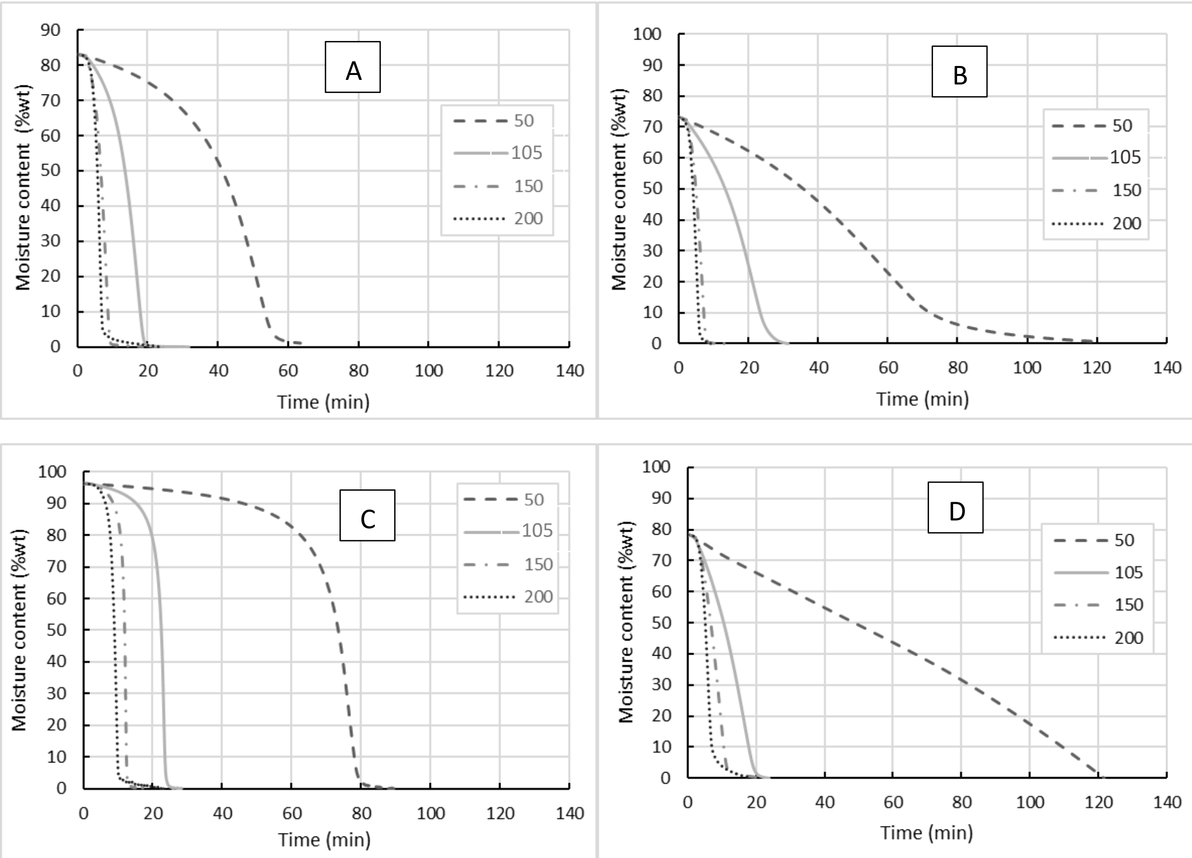
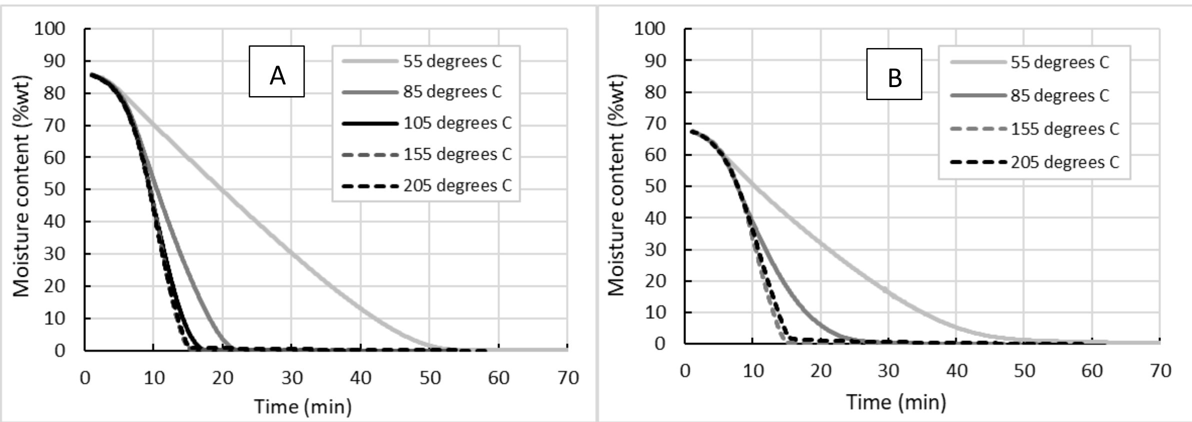


Figure 9. Drying curves obtained in the TGA at UKZN at different temperatures for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D).

Results obtained in the TGA at Swansea University



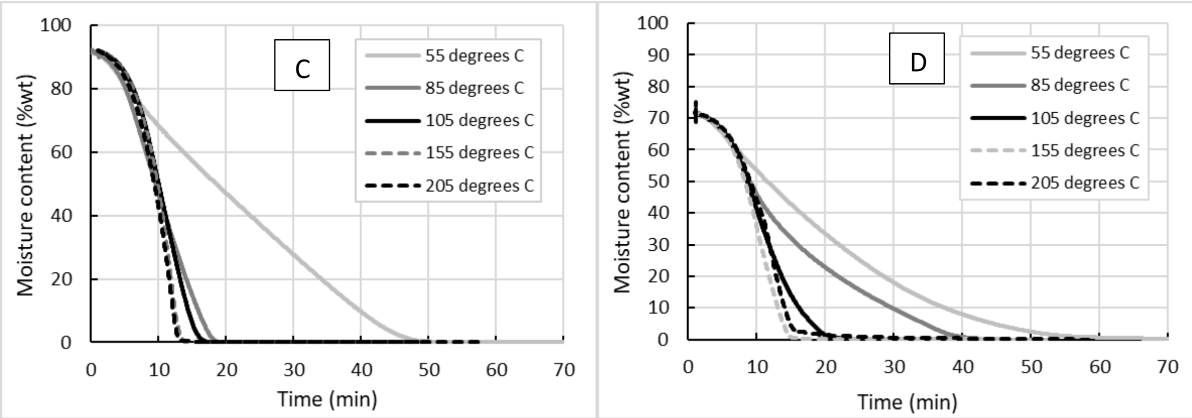


Figure 10. Drying curves obtained in the TGA at Swansea University at different temperatures for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Results obtained in the TGA at Cranfield University

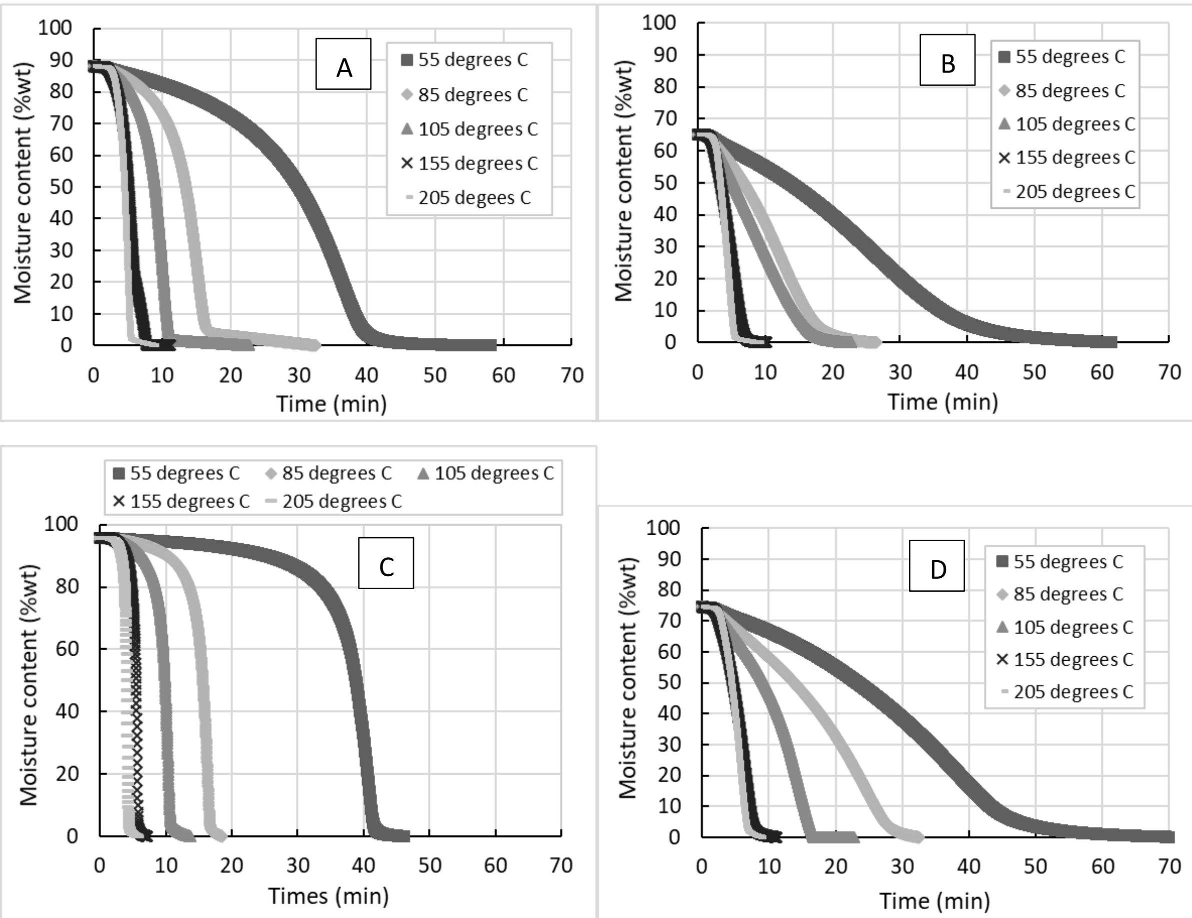


Figure 11. Drying curves obtained in the TGA at Cranfield University at different temperatures for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Results obtained in the moisture analyzer at UKZN

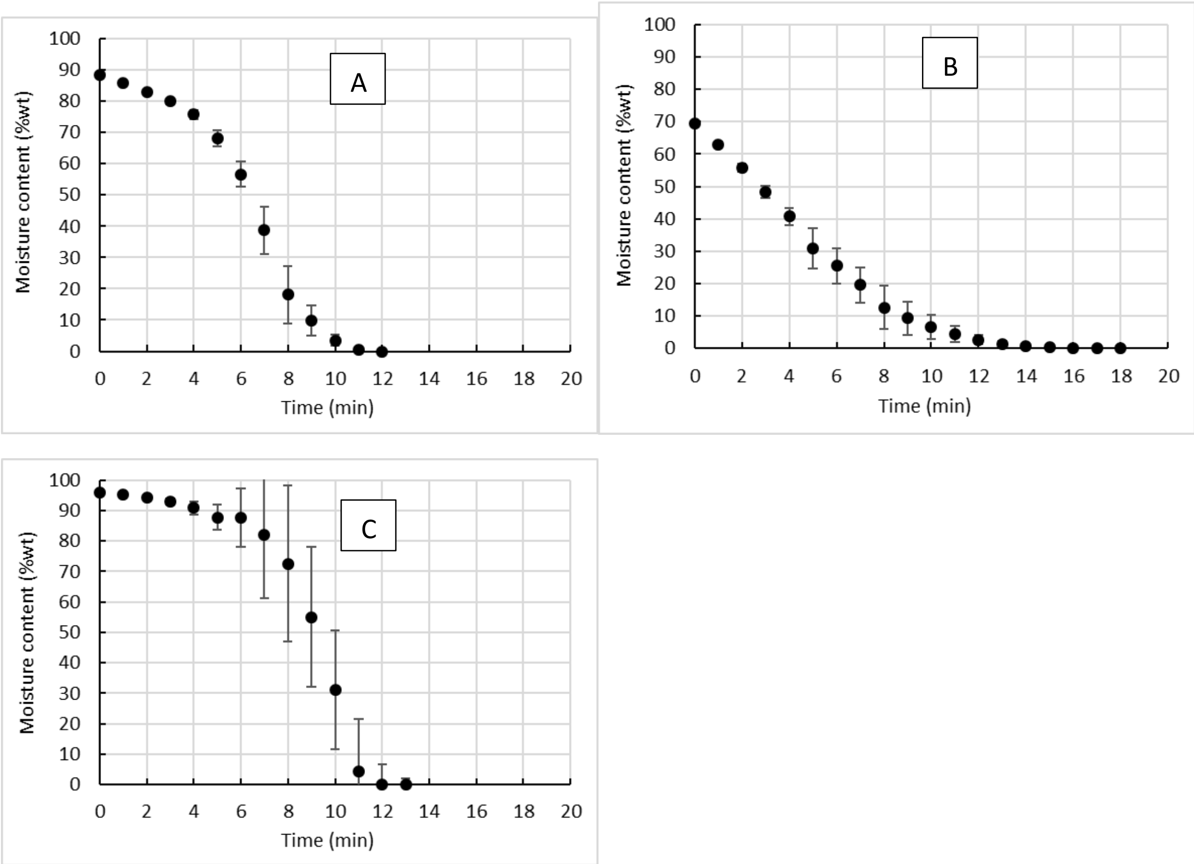


Figure 12. Drying curves obtained in the moisture analyzer balance at UKZN at 100°C for the faecal sludge from ABR (A), UDDT (B) and wet VIP (C)

Discussion

- Comparing Figure 9, Figure 10 and Figure 11, it can be noted that the drying kinetics were different in the TGA from UKZN, Cranfield University and Swansea University, but the trends were similar. For a given type of faecal sludge, the drying kinetics in the Cranfield TGA tended to be the fastest and the slowest in the UKZN TGA, for temperatures equal or lower 100°C. At 150 and 200°C, the differences between the apparatus could not be observed.
- As seen for in the different cases, drying was faster as the temperature was higher. As a function of the drying apparatus and type of faecal material, the complete drying of the sample took from 40 to 120 minutes at 50°C, 10 to 30 minutes at 100°C, 5 to 15 minutes at 150 and 200°C (Figure 9, Figure 10 , Figure 11 and Figure 12). It can be seen that the effect of temperature was diminished at higher temperature. There was a significant difference between 50 and 100°C, but the difference was minimal between 150 and 200°C. Indeed, the effect of temperature can be noted only below 150°C.
- At 50 and 85°C, the fresh faeces dried slower than the faecal sludge samples. Among the faecal sludge samples, the UDDT sludge dried slightly slower than the wet VIP and ABR samples, which dried at approximately the same rate. Above 100°C, all the faecal samples exhibited approximately the same rate.
- The effective diffusivities, which is a parameter lumping various internal mass transfer phenomena (such as capillary flow, liquid and vapour diffusion, material movement due to

thermal or pressure gradients, etc…) were calculated from the TGA results from Cranfield University using the classical approach for a flat slab. The results are summarized in Table 4. It can be seen that the effective diffusivities are in the order of 10^{-6} or 10^{-7}, with an activation energy between 20 and 30 kJ/mol. These results can be useful for the modelling of faecal sludge drying.

Table 4. Effective diffusivity measured from the TGA experiments at Cranfield University

Temperature (°C)	Effective Moisture Diffusivity (m^2/s)			
	ABR	**HF**	**UDDT**	**wet VIP**
55	$3.4 \cdot 10^{-7}$	$3.8 \cdot 10^{-7}$	$5.1 \cdot 10^{-7}$	$3.2 \cdot 10^{-7}$
85	$7.9 \cdot 10^{-7}$	$5.5 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$7.9 \cdot 10^{-7}$
105	$1.3 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$
155	$4.2 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$	$3.9 \cdot 10^{-6}$
205	$7.6 \cdot 10^{-6}$	$9.9 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.0 \cdot 10^{-6}$
Activation Energy (kJ/mol)	28	30	21	27

Conclusions

- Fresh faeces dried slower than faecal sludge at drying temperatures lower than 100°C. Drying above this temperature did not yield to any significant difference on the kinetics between faecal samples from different sources.
- Increasing drying temperature enabled to reduce the drying time, however above 150°C there was no significant improvement.

Heat of drying

Motivation

The heat of drying indicates the energy input required to dry the faecal matter. Usually, the heat of drying is approximated to the latent heat of water vaporization. However, this assumption may be not precise in the case of faecal sludge and fresh faeces where the moisture could be tightly linked to the solid structure. Hence, supplementary energy would have to be required to break these bonds, in addition to the water – water molecule bounds.

An accurate value of the heat of drying is required for precise heat and mass balance, which is necessary for the design, operation and optimization of drying technology, as well as for the assessment of the dryer performance.

Experimental procedure

The heat of drying was calculated using the TGA at UKZN and Swansea. These devices offer the possibility to measure simultaneously the variation of the mass of the sample and the heat flux consumed or released during the transformation. In the case of the TGA at UKZN, the apparatus includes a differential thermal analysis (DTA) from where the heat flux was deduced by the difference of temperature measured between the sample and a reference. In the case of the TGA at Swansea University, referred as simultaneous thermal analyzer (STA), the TGA includes a differential scanning calorimetry where the heat flux was directly calculated from the difference between the heat required to increase the sample and reference to a given temperature.

The heat of drying was then calculated during the TGA drying experiments at UKZN and Swansea University, in the same operating conditions as those described in the previous section. The heat of drying from the beginning to the end of the transformation was measured in the TGA-DTA at UKZN, where the STA recorded the heat of drying at each instant of the process at Swansea University.

Results

Results obtained in the TGA-STA at UKZN

Table 5. The average heat of drying measured in the TGA-DTA at UKZN for the different faecal samples and drying temperatures

Temperature [°C]	Heat of Drying [kJ/kg water removed]		
	ABR	UDDT	wet VIP
50	4,000 ± 500	3,000 ± 0	2,600 ± 200
100	4,800 ± 400	5,700 ± 600	4,100 ± 500
150	2,400 ± 300	6,100 ± 100	3,700 ± 100
200	4,900 ± 600	5,600 ± 0	4,300 ± 900

Results obtained in the STA at Swansea University

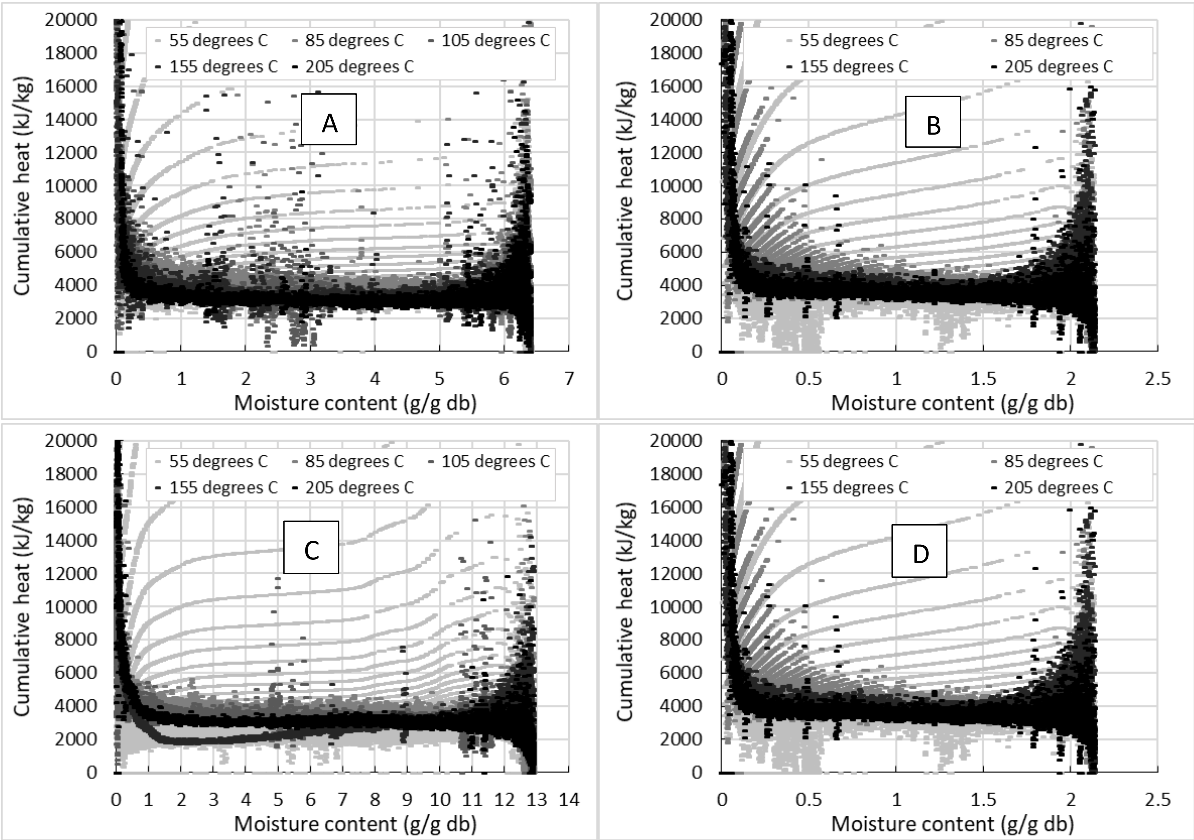


Figure 13. Heat of drying measured by the STA at Swansea University during the drying of faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D) at different temperatures

Discussion

- In Figure 13, we can observe that, for all samples, the heat of drying remained fairly constant along with the transformation, until achieving a moisture content from where it started to increase exponentially. This inflexion point occurred at a moisture content of approximately 0.3 - 0.4 g/g in dry basis (equivalent to 20-30 %wt) for the ABR, UDDT and fresh faeces samples, and a moisture content of 1 g/g in dry basis (equivalent to 50%wt) for the VIP samples. The heat of drying tended towards a vertical asymptote at moisture contents lower than 0.1 g/g in dry basis (equivalent to 10%wt). The exponential increase of the heat of drying could indicate an important increase of the moisture boundedness in the material. The vertical asymptote could mark the end of drying. Note that at the beginning of the experiment, the heat of drying fluctuated considerably, which could be due to the unsteady conditions at this stage.
- No trend was observed concerning the temperature and type of faecal sludge. In most of the cases, the heat of drying varied between 3,000 to 5,000 kJ/kg. A similar result was obtained for the results at UKZN (Table 5).

- The heat of drying was higher than the latent heat of water vaporization (2,260 kJ/kg) for most of the faecal samples.

Conclusions

- The heat of drying was similar among all the faecal samples and higher than the latent heat of pure water vaporization, suggesting a certain level of boundedness of the moisture with the solid structure from the material.
- The heat of drying rose drastically at the last stage of drying, probably due to the high boundedness of the remaining moisture with the solid. Drying could be stopped before reaching this stage, which occurred approximately below 30%wt moisture content, to avoid to consume a high amount of energy to remove the residual moisture that is already found in small quantities.

Drying emissions

Motivation

Faecal material is well known for its emission of unpleasant odours, which is provoked by volatile organic or inorganic compounds. During drying, the effect of heat can provoke a substantial increase of the volatilization of these olfactory compounds, which can subsequently leave the material with the evaporated moisture in the exhaust air stream. Therefore, the gas exhaust from a drying process can contain a concentrated amount of olfactory compounds that can intensify the bad odours at the surroundings. Apart from the odour nuisances, the exhaust from a drying process can contain compounds that can be potentially hazardous for the environment and human health above a threshold, such as H_2S.

For these reasons, it is important to analyze and characterize the composition of the exhaust gas from a drying process. This way, strategies to mitigate these inconveniences could be implemented. Moreover, the gas composition analysis could also allow identifying certain transformations or reactions during drying.

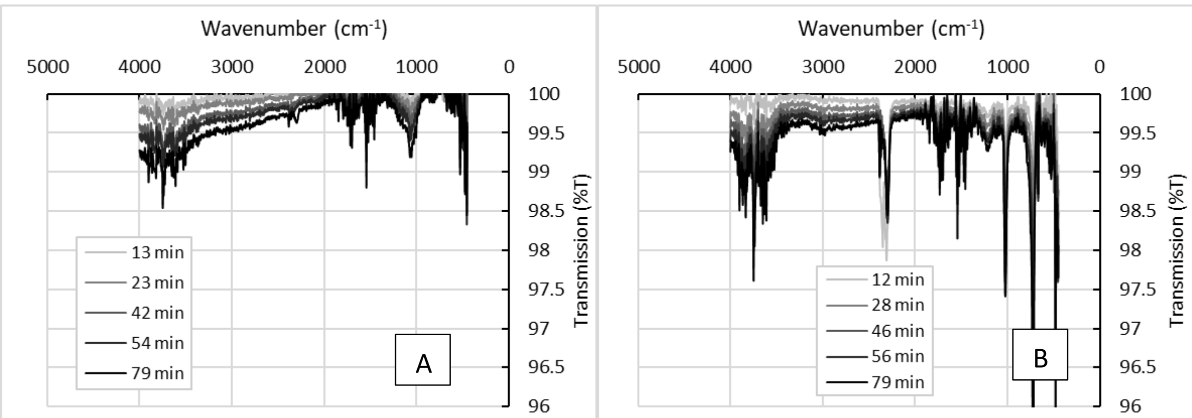
Experimental procedure

The STA at Swansea University was hyphened to gas chromatography-mass spectroscopy (GC-MS) and a Fourier transformation Infrared radiation (FTIR) analyzer, in order to identify the compounds released during the drying experiments. Unfortunately, the GC-MS broke down before the experiments and could not be utilized. The FTIR analysis was performed at different instants during the STA experiments.

The TGA at Cranfield University was coupled to GC-MS during the drying experiments. However, no compounds could be identified apart from water, which was presumed to be due to the low volatile compounds concentrations in the gas stream that were below the detection threshold.

Results

Results obtained in the FTIR analysis during the STA tests at Swansea University (55°C)



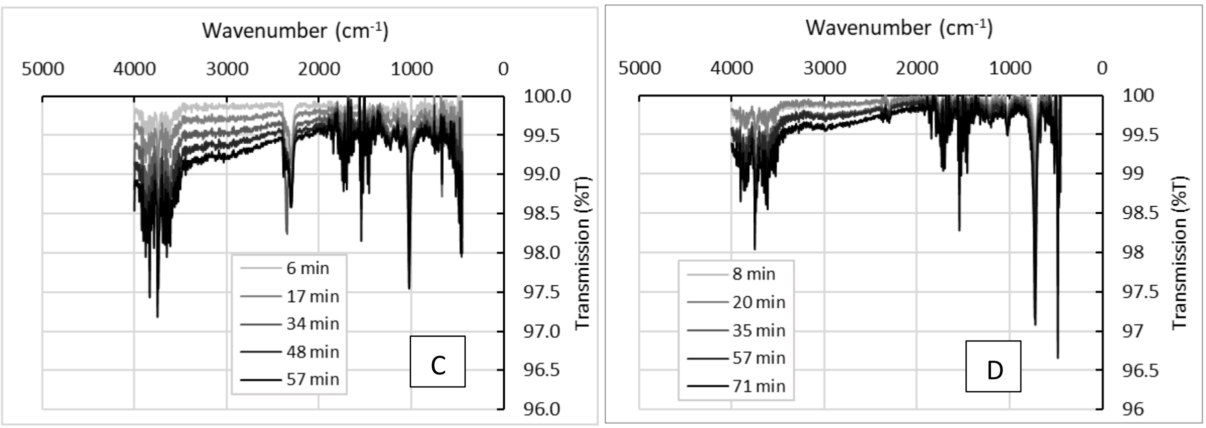


Figure 14. Transmittance spectrum measured by the FTIR analyzer at different instants during the drying STA tests at 55°C

Results obtained in the FTIR analysis during the STA tests at Swansea University (155°C)

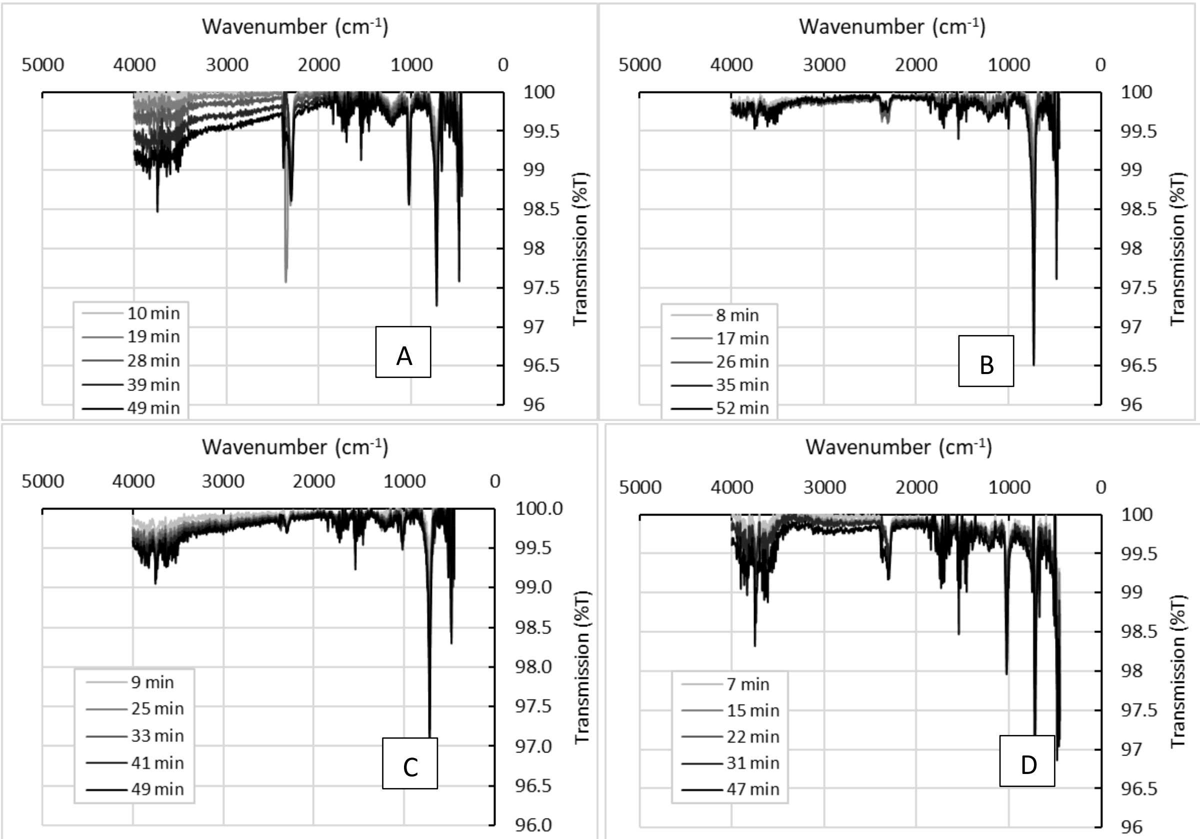


Figure 15. Transmittance spectrum measured by the FTIR analyzer at different instants during the drying STA tests at 155°C

Discussion

- In Figure 14 and Figure 15, the main regions identified in the transmittance spectrum were as follow:
  - 4,000 to 3,400 cm^{-1} corresponding to the stretch of the bound O-H from the water molecule;
  - 2,400 to 2,250 cm^{-1} corresponding to the carbon dioxide presence;

    - 1,800 to 650 cm-1 corresponding to the presence of organic compounds, such as ethers, esters, alcohols, aromatics, amines and alkenes, and water molecule scissoring.
- No particular trend was observed as a function of time, temperature or type of faecal material under the explored conditions. Further experiments would be required to establish trends as a function of the operating conditions and feedstock, as it was difficult to arrive to this level of analysis with the available data. Indeed, due to time constraints and the lack of calibration of the FTIR analyzer relative to the identified compounds, it was not possible to obtain a more precise identification and quantification of the identified compounds.

Conclusions

- The exhaust gas from faecal matter drying was composed of carbon dioxide and organic compounds, apart from the evaporated moisture.
- Due to the difficulty or impossibility to analyze and interpret the data obtained during the TGA, which is arisen from the low amount of samples used during these analyses, it is recommended to conduct gas analysis tests in the future in devices allowing considerably larger amounts of sample.

Thermal degradation

Motivation

The heat supplied during drying to evaporate the moisture from the faecal matter can potentially degrade the solid structure of the material, which can affect the quality of the dried product for its reuse. It is well known that increasing the heating flux increases the drying performance; however, this also increases the risk of the thermal degradation of the material, hence the need to find a tradeoff. It is then important to determine from which temperature the material can be thermally degraded. This information can be useful for the operation of dryers if thermal degradation wants to be avoided.

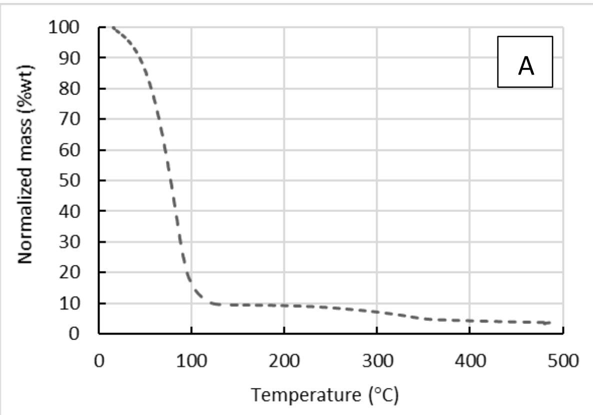
Experimental procedure

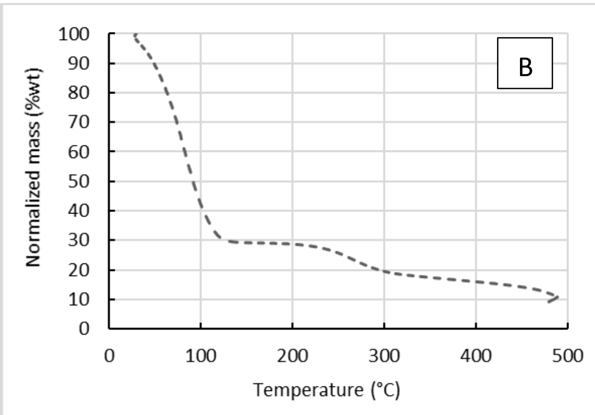
The thermal degradation of the faecal feedstock was firstly investigated using the TGA-DTA at UKZN in dynamic mode. On the contrary to the previous TGA tests where drying was performed at constant temperature (isothermal test), here the drying chamber was heated during the entire experiment at a rate of 5°C/min, from ambient temperature until 500°C. The mass of sample and carrier gas flowrate remained the same between the isothermal and dynamic tests, as well as the type of feedstock employed.

The thermal degradation was further studied by measuring the volatile solid content and calorific value of faecal samples that were dried in an oven at 50, 100, 150 and 200°C. Indeed, a decrease of the volatile solid content and gross calorific value would reflect a loss of organic material due to thermal degradation. The volatile solids content was measured based on the Standard Method for the Examination of Water and Wastewater, whereas the calorific value was measured using a calorimeter *Parr 6200*. Two distinct batches of tests were carried out for this type of experiment. In the first batch, the faecal samples were completely dried in the oven and then analyzed. In the second batch, the samples were analyzed after being dried in the oven at different moisture content (60, 40, 20 and 0%wt) and using the same temperatures than in the first batch (namely 50, 100, 150 and 200°C).

Results

Results obtained during the dynamic tests in the TGA at UKZN





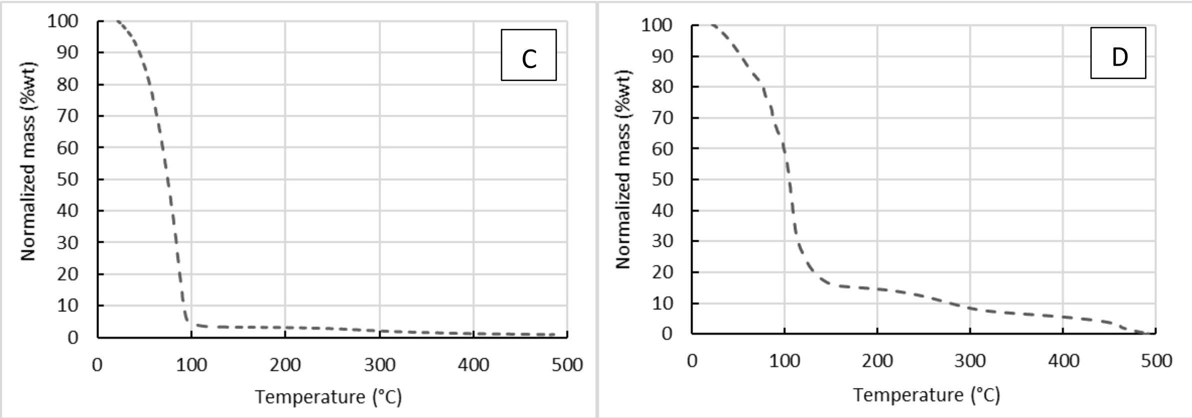


Figure 16. Normalized mass of the sample with respect to the initial value as a function of temperature for the faecal sludge from ABR (A), UDDT (B), dry VIP (C) and fresh faeces (D)

Volatile solids content of the faecal samples measured after oven drying at different temperatures at UKZN (first batch)

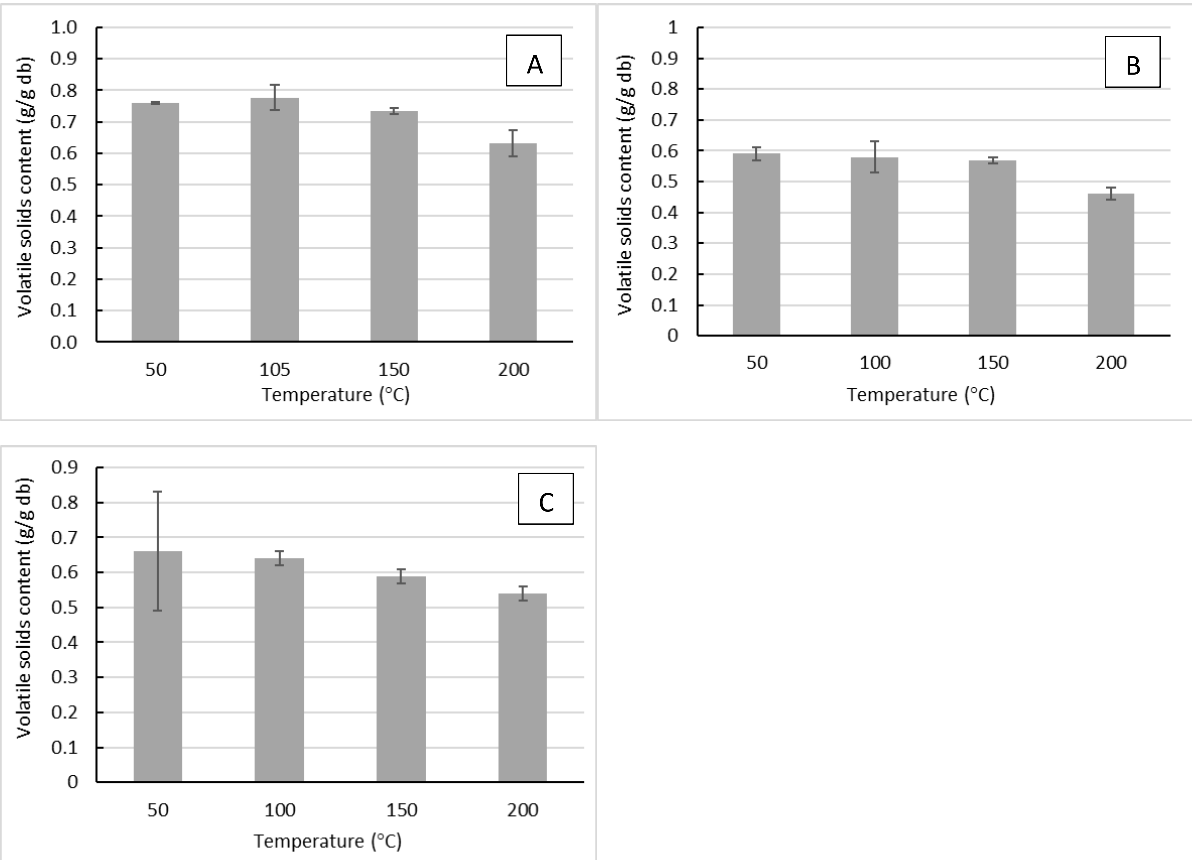


Figure 17. Volatile solids of the sample after complete oven drying at different temperatures, for the faecal sludge from ABR (A), UDDT (B) and wet VIP (C)

Calorific value of the faecal samples measured after oven drying at different temperatures at UKZN (first batch)

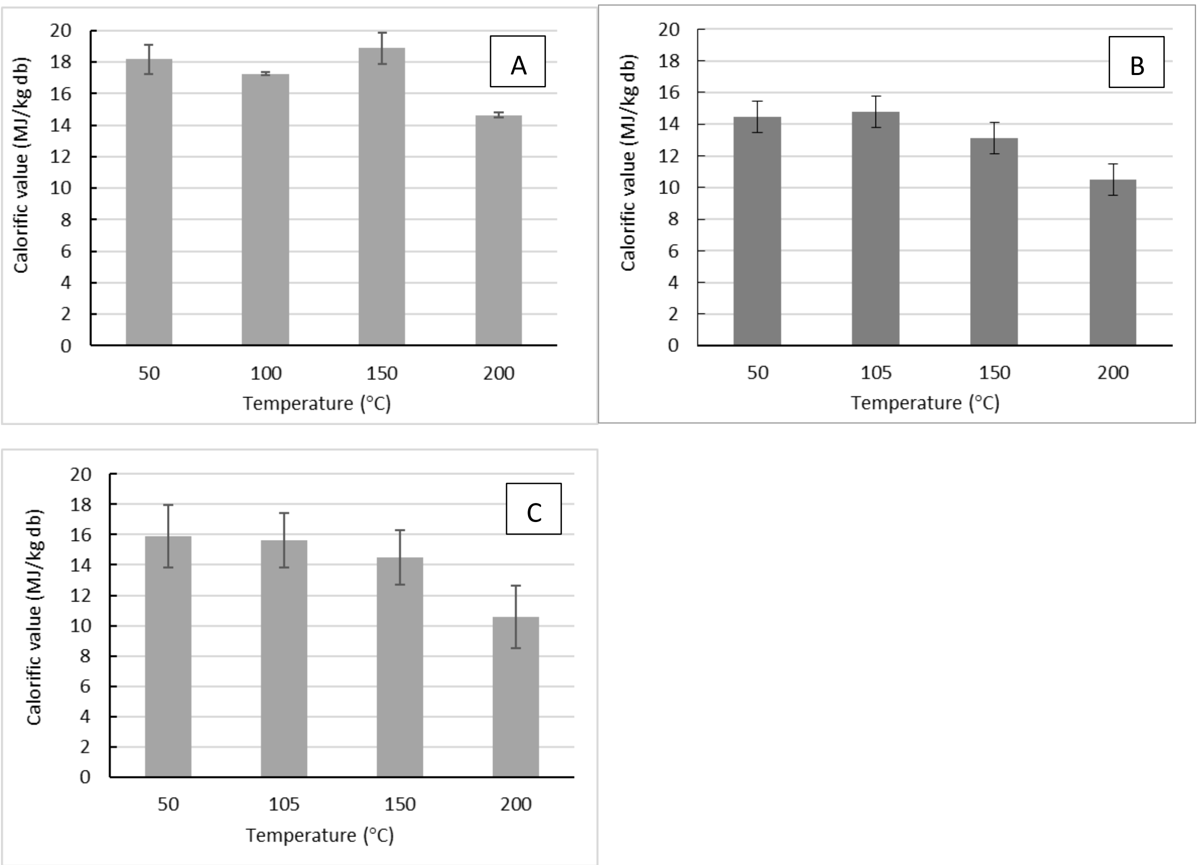
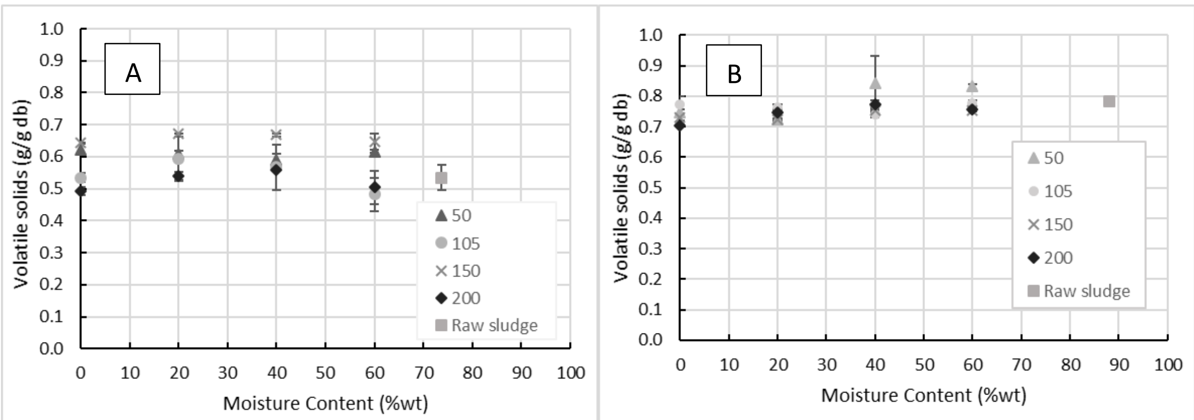


Figure 18. Gross calorific value of the sample after complete oven drying at different temperatures, for the faecal sludge from ABR (A), UDDT (B) and wet VIP (C)

Volatile solids content of the faecal samples measured after oven drying at different temperatures at UKZN (second batch)



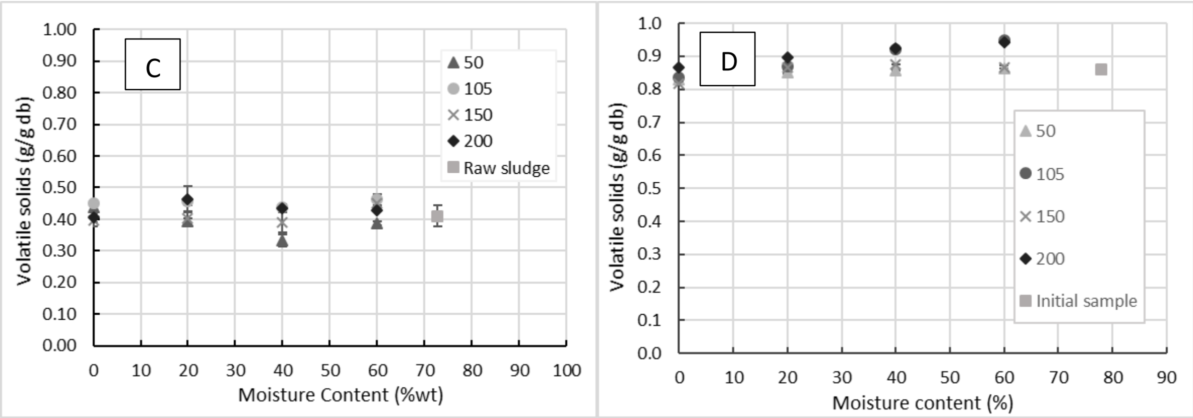


Figure 19. Volatile solids content versus moisture content at different drying temperatures, for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Calorific value of the faecal samples measured after oven drying at different temperatures at UKZN (second batch)

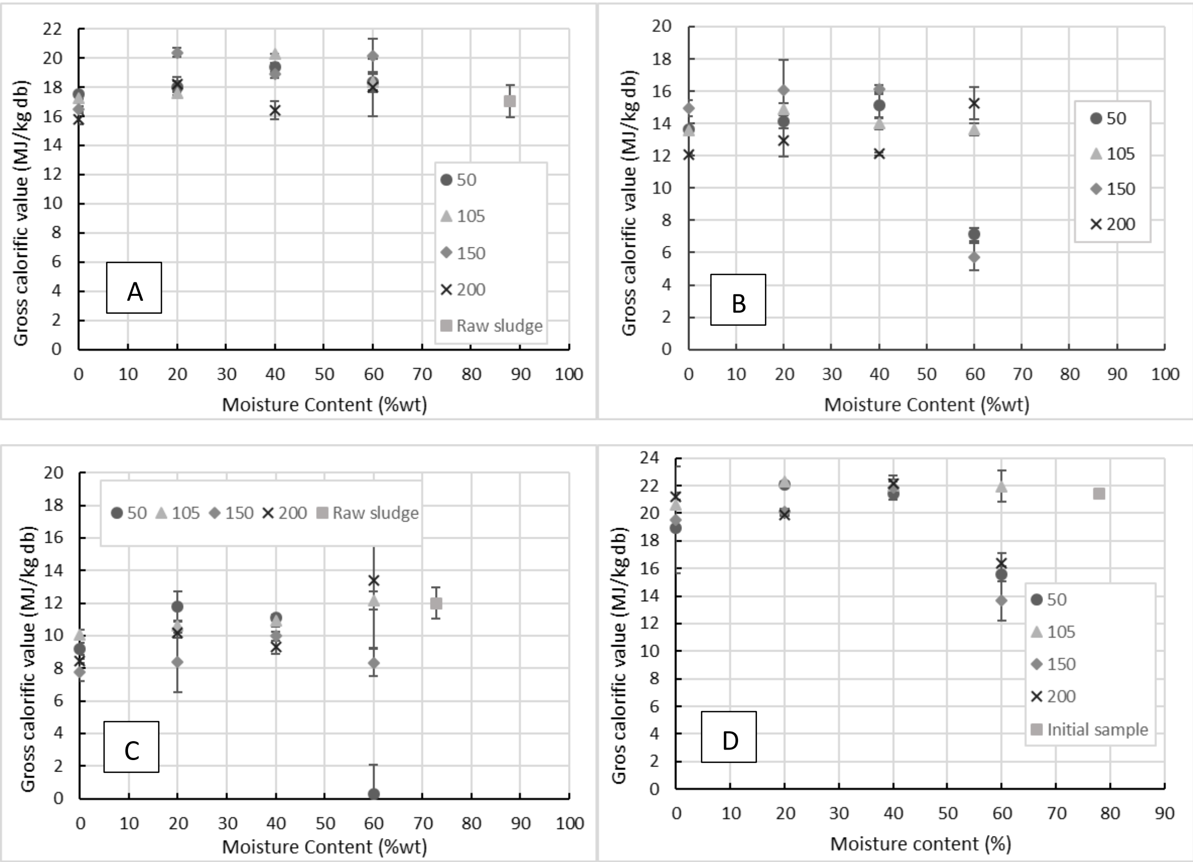


Figure 20. Gross calorific value versus moisture content at different drying temperatures, for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Discussion

- It can be seen in Figure 16 that the mass of all faecal samples experienced two drops while it was heated from ambient temperature to 500°C. The first drop of mass, corresponding to the drying stage, occurred from the beginning of the experiment and finalized around 100 - 150°C when the sample was likely completely dried. During this stage, the sample lost the major part of its mass. After that, the mass of the sample remained constant with the increase of temperature until reaching approximately 220°C, from where the second drop of mass started. This decrease in mass was probably initiated by the thermal degradation of the sample (pyrolysis and oxidation) and it was achieved after all the organic compounds were consumed (except for the UDDT sample for which the thermal degradation seemed to be in course after the end of the test).
- During the first batch of the oven dried sample analysis, it can be noted a slight decrease of the volatile solid content and gross calorific value at 200°C, whereas these parameters remained the same at lower temperatures (Figure 17 and Figure 18). This decrease could be explained by a mild thermal degradation of the samples at 200°C.
- During the second batch of analysis, the volatile solids content and gross calorific values did not display any significant difference across the different moisture contents and temperature, except for the wet VIP sludge which was the only sample to exhibit a slight gross calorific value decrease at 200°C after complete drying (Figure 19 and Figure 20). Therefore, almost no thermal degradation was observed in this batch of experiments, on the contrary to the first one.

Conclusions

- The thermal degradation of all the faecal samples, regardless of their source, occurred above approximately 220°C.
- Thermal degradation of faecal matter could start even at a lower temperature, namely 200°C, but this could not be verified with certainty through the experimental results.

Sorption isotherms and water activity

Motivation

The sorption isotherms display the moisture content of a moist material as a function of relative humidity at a given temperature. Formally, drying is driven by the difference of water activity between the moist solid and the surrounding air. In other terms, drying occurs because the vapour pressure of the moisture in the moist solid is superior to that from the water vapour in the surrounding air. This vapour pressure gradient leads to the transfer of moisture from the solid to the air as vapour water after evaporation. Drying stops when the thermodynamic equilibrium is reached, i.e. when the vapour pressure in the solid and surrounding air are equal (or equal water activities). This event occurs when the solid reaches what is known as the equilibrium moisture content.

The sorption isotherms present two components: a desorption curve corresponding to drying and adsorption isotherm corresponding to regain of moisture in the case of a hygroscopic material. It is important to characterize the sorption isotherms to determine the equilibrium moisture content, i.e. the maximum moisture removal that can be obtained after drying at a given relative humidity and temperature. At the equilibrium moisture content, the relative humidity of the air is equal to the water activity in the solid. Therefore, the sorption isotherms would allow determining the water activity in the solid as a function of moisture content.

Water activity, which is defined as the ratio of the vapour pressure of moisture in the faecal material to that from pure water at the same temperature, can give useful estimations of the level of boundedness of moisture with the solid structure of the faecal material. A water activity equal to 1 (maximum value) means that the moisture in the material behaves as pure water, so we can expect that most of the faecal matter is unbound. On the opposite, low values of water activity (approaching 0) would reflect moisture that is tightly linked to the solid structure, hence bound moisture.

Furthermore, the water activity is an indicator of the microbial activity in the material. Indeed, the microbes require of available moisture for their vital metabolism reactions. Each type of microorganism can tolerate a minimum value of water activity, below which the microbial population can not develop further and is susceptible to die. Tables with the water activity values required to deactivate a given type of microorganism were developed in the food industry.

Experimental procedure

Three different methods were employed to determine the sorption isotherms (experiments performed at UKZN).

In the first method, a given amount of sample was placed in sealed jars containing a given saturated salt solution to control the relative humidity to a given value at ambient conditions. The employed saturated salt solutions were potassium hydroxide, calcium chloride, magnesium nitrate, potassium iodide, ammonium sulphate and potassium nitrate, leading to relative humidities of 6, 30, 49, 64, 80 and 95% respectively. After the mass of samples inside the jar stabilized after its desiccation, the equilibrium moisture content was measured using a moisture analyzer balance *Radwag Max 50*, and the desorption isotherm was plotted. This experiment was also conducted in the reverse mode using a bone-dried sample and exposing them to the different relative humidities, in order to measure its gain in moisture and plot the adsorption isotherm.

In the second method, the faecal samples were dried in an oven at different moisture content, namely 60, 40, 20 and 0%wt, at 50, 100, 150 and 200°C. The water activity of the dried samples was measured by a water activity analyzer *AquaLab Tunable Diode Laser-TDL*. The third method was similar to the previous one with the difference that the sample was dried at in a moisture analyzer balance *PCE-MB Series* at 100°C. For both methods, the water activity was measured at ambient temperature.

Results

Sorption isotherms using the saturated salt solution method

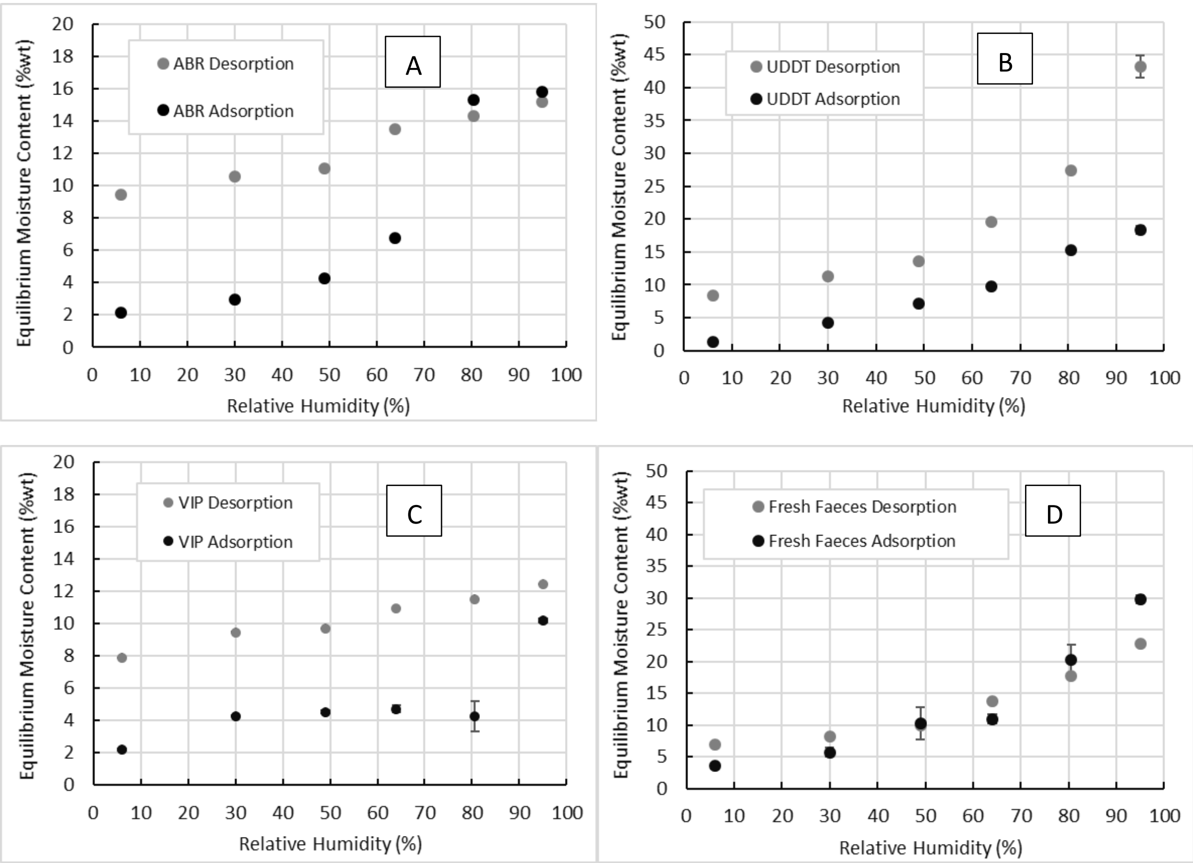
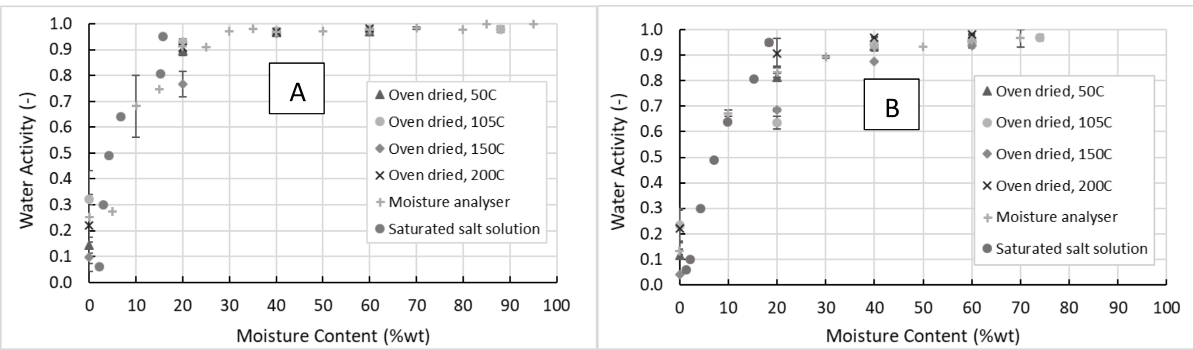


Figure 21. Desorption and adsorption isotherm curves for the sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D) at ambient conditions

Water activity as a function of moisture content for the three tested methods



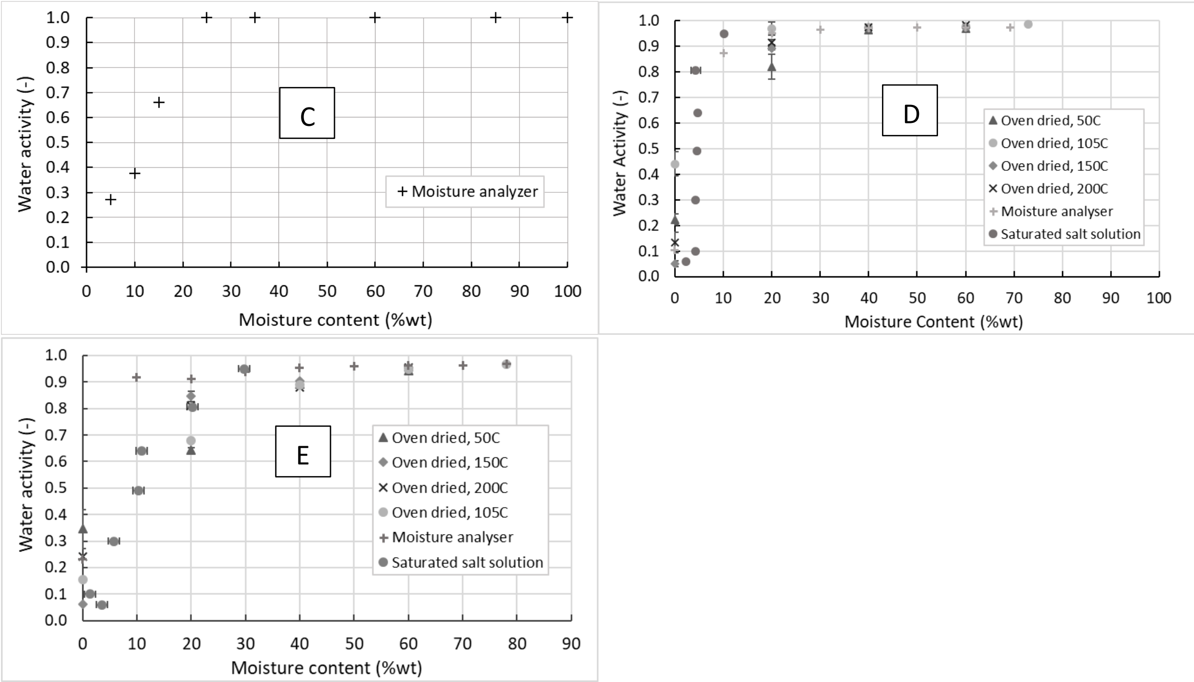


Figure 22. Water activity versus moisture for the sludge from ABR (A), UDDT (B), wet VIP (C), dry VIP (D) and fresh faeces (E) using different methods

Discussion

- In Figure 21, it can be observed that the faecal samples can be dried at low moisture content even at high relative humidities (desorption curves). At the highest relative humidity, namely 95%, the wet VIP and ABR samples could be dried up to 10 – 15%wt moisture content, and fresh faeces samples to around 25%wt and UDDT sludge to around 45%wt.
- It can also be noted in Figure 21 that bone dried faecal material could regain moisture if placed in a humid environment (adsorption curves). For the faecal sludge samples, the moisture content of the dried sludge could increase up to 15% if placed at an environment with 95% relative humidity. In the case of fresh faeces, the regain of humidity was higher (30%wt moisture content).
- The desorption and adsorption curves in Figure 21 were different, suggesting different mechanisms for the removal and regain of moisture from the surface of the faecal material, except for fresh faeces for which both curves were almost identical.
- In Figure 22, the water activity decreased as moisture content was reduced for all the samples. This decrease in water activity was low or null until reaching 20 - 30%wt moisture content, from where the water activity starts to drop drastically. This result suggests that, from this point, the remaining moisture was strongly bonded to the solid structure. Above a moisture content of 20 - 30%wt, the water activity was comprised between 0.9 and 1.0, suggesting a certain level of moisture boundedness within the material.
- It can be noted in Figure 22 that the different methods to determine the water activity lead to a similar pattern. Likewise, no trend was observed as a function of the type of faecal matter. These results entail that the moisture boundedness was similar between the different types of faecal material and was not affected by the drying conditions. Nonetheless, at high moisture content,

Conclusions

- Even at high relative humidities, the faecal material could be dried to relatively low moisture content (below 50%wt).
- The faecal material is hygroscopic, so it could be remoisturized if placed in a humid environment.
- A moisture content around 20-30%wt marked a transition in the boundedness of moisture within the material. Above this point, the moisture was probably unbounded and moderately bounded to the solid matrix. Below this point, the moisture started to be strongly bonded to the solid material, and its boundedness increased as drying progressed.
- The type of faecal material and drying conditions did not have a significant influence on moisture boundedness.

Dewaterability

Motivation

The removal of moisture during drying demands of high heat supply because of the high energy required for moisture evaporation. The removal of excess unbounded or weakly bounded moisture through mechanical dewatering could reduce the energy requirements for the drying process, leading to lower running costs and smaller drying equipment. It is then of high importance to determine the removal of moisture that could be potentially achieved through dewatering.

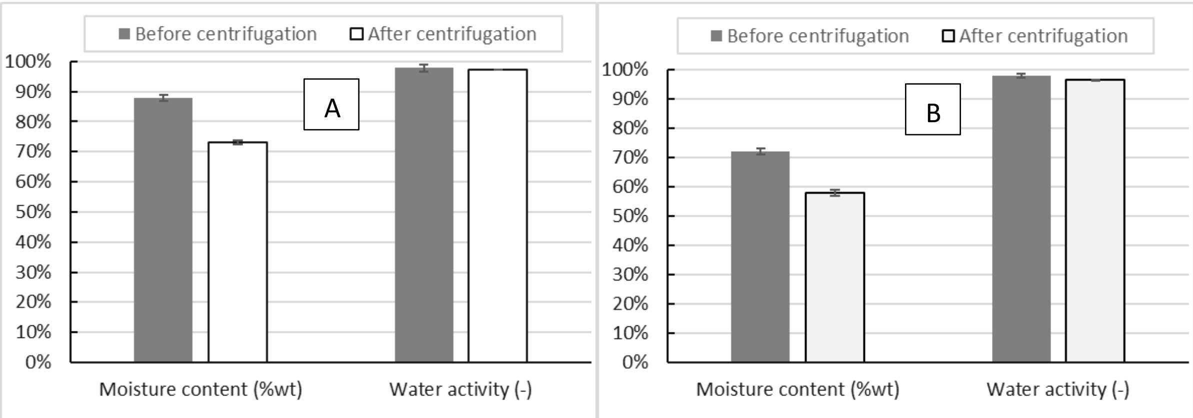
Experimental procedure

The faecal samples dewaterability was assessed through centrifugation tests in a centrifuge *HERMLE Z323* with 40 g of sample per centrifugation tube (experiments performed at UKZN). A first batch of tests was performed with UDDT and wet VIP samples centrifuged during 20 minutes at a rate of 6,000, 8,000 and 10,000 RPM. A second batch of tests was then conducted with ABR, dry VIP and fresh faeces samples centrifuged during 120 minutes at a rate of 5,000 RPM. After centrifugation, the moisture content and water activity of the solid residue was analyzed.

Note that the centrifugation conditions changed between the first and second batch because of the change of the rotor to a less powerful one. Therefore, the centrifugation time was increased to compensate for the decrease in the rotation capacity. It was verified that centrifugation at 10,000 RPM for 20 minutes led to the same result that centrifugation at 5,000 RPM for 120 minutes.

Results

Results of the first batch of centrifugation tests



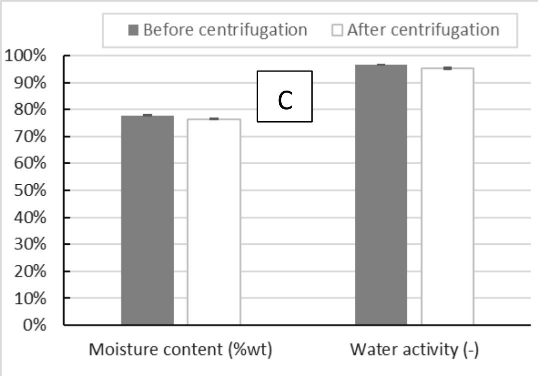


Figure 23. Moisture content and water activity before and after centrifugation for the sludge from ABR (A), dry VIP (B) and fresh faeces (C)

Results of the second batch of centrifugation tests

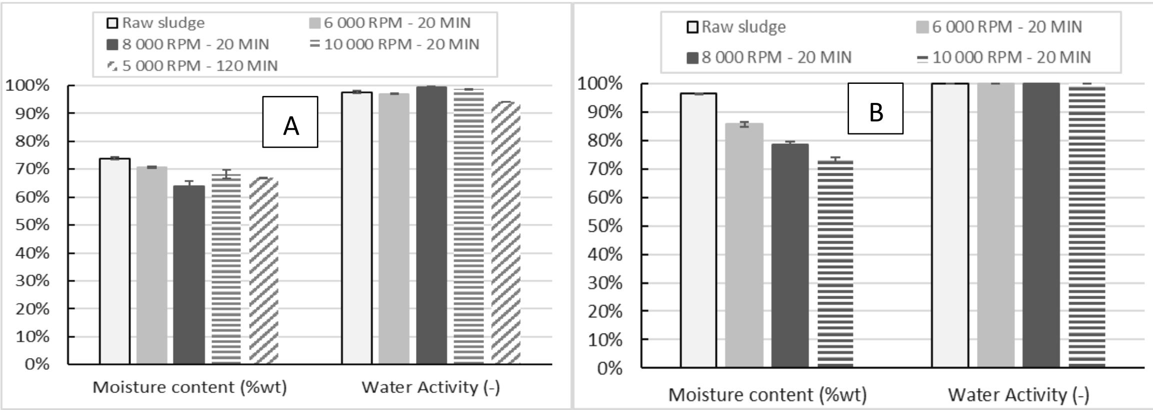


Figure 24. Moisture content and water activity before and after centrifugation for the sludge from UDDT (A) and wet VIP (B)

Discussion

- According to Figure 23 and Figure 24, centrifugation could reduce the moisture content to values around 70% for the ABR, UDDT and wet VIP samples, and 60% for the dry VIP samples. The moisture removal was more important as the initial moisture content was higher. No significant reduction of moisture with centrifugation was observed for fresh faeces.
- As seen in Figure 23 and Figure 24, centrifugation does not significantly affect the water activity, which varied between 0.9 and 1 for all samples. Therefore, dewatering allowed removing only the unbound or loosely bounded moisture.

Conclusions

- Faecal sludge could be dewatered, in particular those with a liquid consistency. The dewatering of semi-solid sludge was considerably lower. This result could be explained by a higher amount of unbounded moisture the faecal sludge samples with a liquid consistency.
- The maximum moisture removal that could be achieved through centrifugation was comprised between 60 and 70% moisture content.
- Fresh faeces could not be dewatered, suggesting that this type of material did not present any unbound moisture.

Thermal properties

Motivation

The thermal properties of the material are an important element for the heat balance calculations that can serve to the design and operation of thermal drying technologies. The thermal properties of faecal material can change during the drying process, which needs to be considered in the heat balance for more accurate calculations.

Experimental procedure

Faecal samples were dried in the oven at different moisture content (60, 40, 20 and 0%wt) at 50, 100, 150 and 200°C and then their thermal properties were analyzed using a *C-Therm TCi* analyzer. These experiments were conducted at UKZN.

Results

Thermal conductivity results

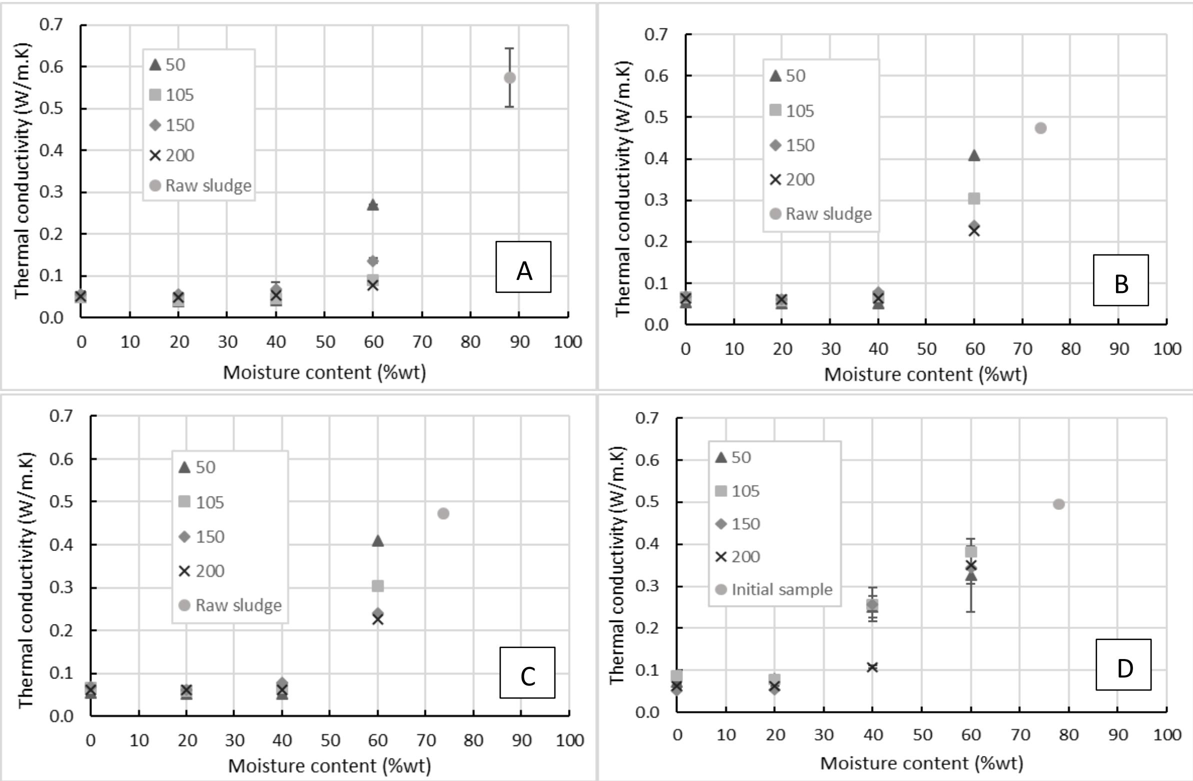


Figure 25. Thermal conductivity versus moisture content at different drying temperatures, for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Heat capacity results

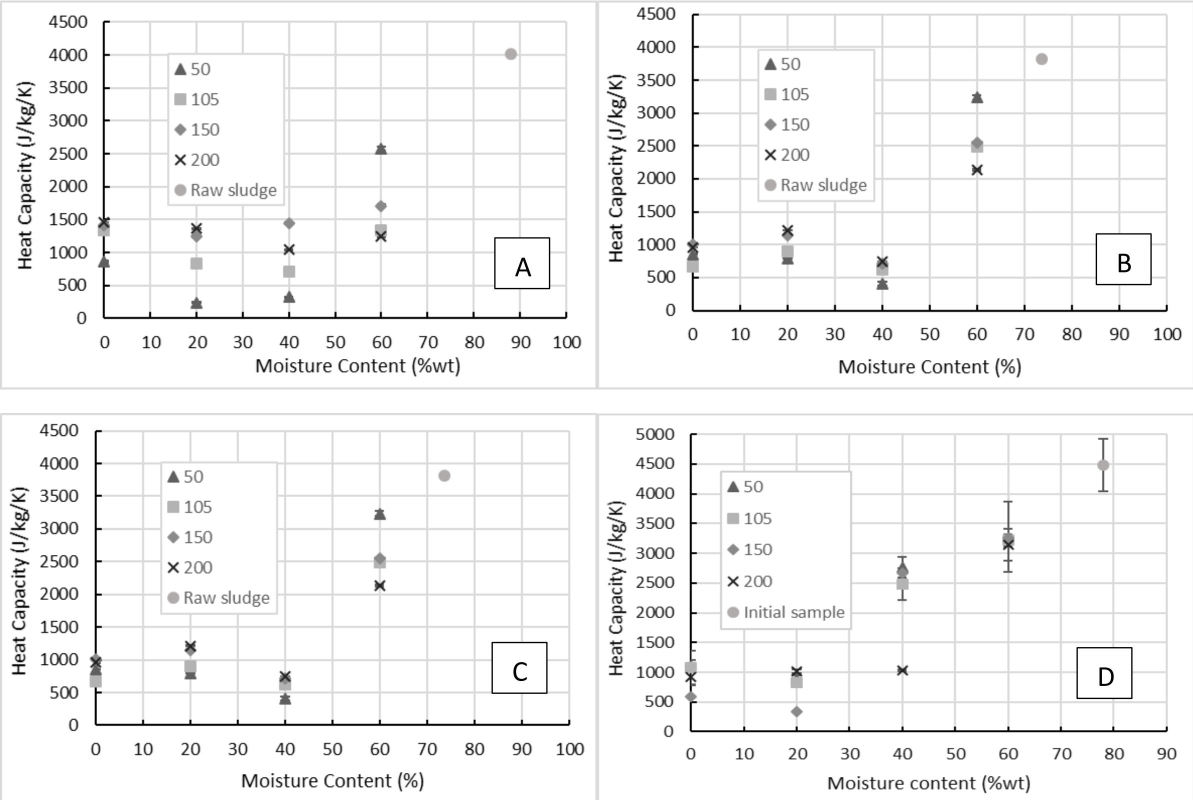


Figure 26. Heat capacity versus moisture content at different drying temperatures, for the faecal sludge from ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D)

Discussion

- Figure 25 and Figure 26 show that the thermal conductivity and heat capacity decreased along with the moisture removal until achieving a moisture content of 40%wt, below which the thermal properties remained constant. This trend was the same for all samples and drying temperatures
- The thermal conductivity and heat capacity from the samples before drying were around 0.5 – 0.6 W/m/K and 3,500 – 4,500 J/kg/K, respectively. These values are close to those from pure water, namely 0.6 W/m/K and 4,186 J/kg/K respectively, suggesting that the thermal properties of the initial faecal samples were controlled by the high amounts of moisture in the material. The influence of moisture on the thermal properties was reduced as drying proceeded.
- The thermal conductivity and heat capacity for all samples below 40%wt moisture content dropped to around 0.05 W/m/K and 500 – 1,000 J/kg/K respectively. The final values of the thermal properties (after drying) were similar for the different faecal samples and was not affected by the drying temperature.

Conclusion

- The thermal properties of the faecal material were highly influenced by their high moisture content.
- During drying until 40% moisture content, the influence of moisture in the thermal properties was reduced, causing a decrease of the thermal conductivity and heat capacity. Below 40% moisture content, the influence of moisture ceased and, in consequence, thermal properties remained constant after further drying.

Radiative properties

Motivation

Among the different drying methods, some of them rely on the supply of heat as radiation, such as infrared and solar drying. For the radiative drying technologies, a piece of useful information to know is the amount of radiation that the faecal material is able to absorb.

Experimental procedure

The reflectance and transmittance of the faecal samples (ABR, UDDT, wet VIP and fresh faeces) were measured in a UV-Vis-NIR spectrophotometer *Perkin Elmer Lambda 750S*, at Swansea University. The measurements were performed for different thickness of sample, namely 1, 2, 3 and 4 mm. The data collection range was done in a wavelength interval of 250 to 2,500 nm, at a data collection interval of 5 nm and a scan speed of 1,196.19 nm/min. The studied wavelength interval covered most of the solar irradiance spectrum, including the ultraviolet, visible light and part of the near-infrared (NIR) regions.

Results

Reflectance results

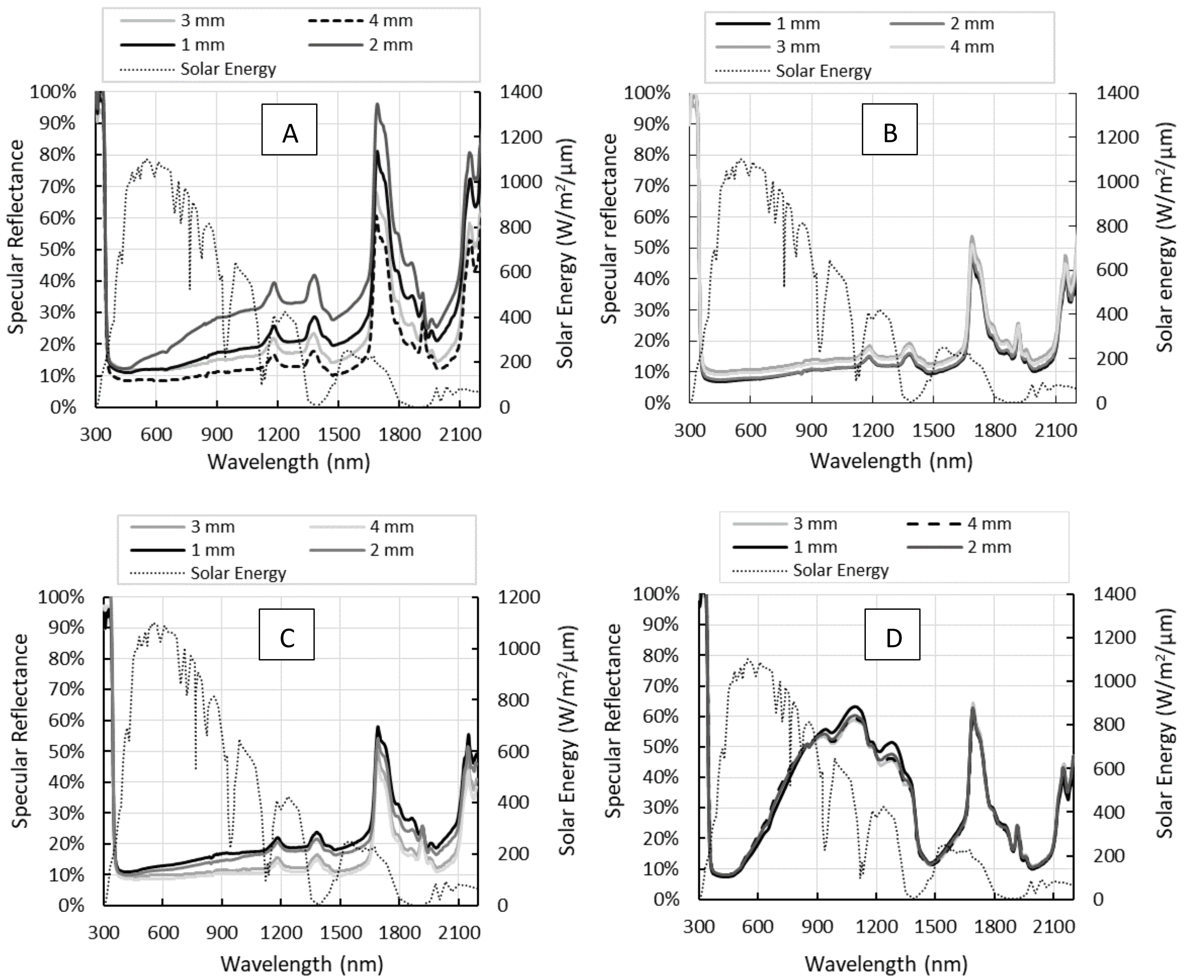


Figure 27. Reflectance for different thickness of ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D) sample, compared to the solar irradiance spectrum

Transmittance results

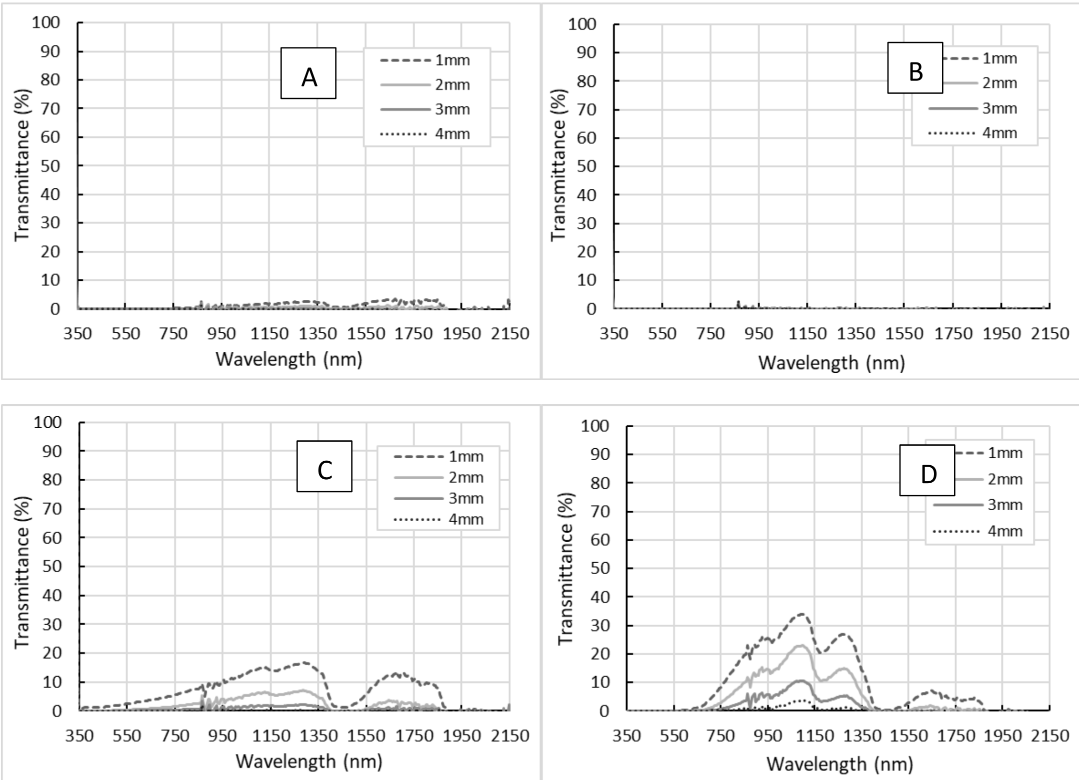


Figure 28. Transmittance for different thickness of ABR (A), UDDT (B), wet VIP (C) and fresh faeces (D) samples

Discussion

- As seen in Figure 27, the ABR, UDDT and wet VIP faecal sludge samples in overall exhibited a low reflectance with most of the values lower than 20%. The only area with high reflectance was situated in a narrow range of the NIR region (1,600 – 1,900 nm), with a peak attaining maximum values of 60 to 90% as a function of the sample. In contrast, the fresh faeces presented a relatively high reflectance across the whole spectrum from the analysis, with two peaks attaining up to 60%, in the wavelength intervals of 500 – 1,500 nm and 1,600 – 1,900 nm. The thickness of the sample did not show any clear trend on the reflectivity.
- It can be observed in Figure 28 that the transmittance of the ABR and UDDT samples was almost null, whereas two transmittance peaks, going up to 5 - 30%, were identified for the wet VIP and fresh faeces samples at a wavelength interval of 350 – 1,400 nm and 1,500 – 1,900 nm. The transmittance values were higher for the fresh faeces compared to the wet VIP samples, and increased by decreasing the thickness of the sample.
- The absorbance, deduced from the formula "absorbance = 1 – reflectance – transmittance", varied from 50 to 70% for all the samples.

Conclusions

- The visible and NIR radiation had a low depth of penetration into the faecal material, which was of a few mm or less than 1 mm.
- An absorbance of approximately 60 – 70% could be expected for faecal materials during solar or NIR drying processes.

Surface properties

Motivation

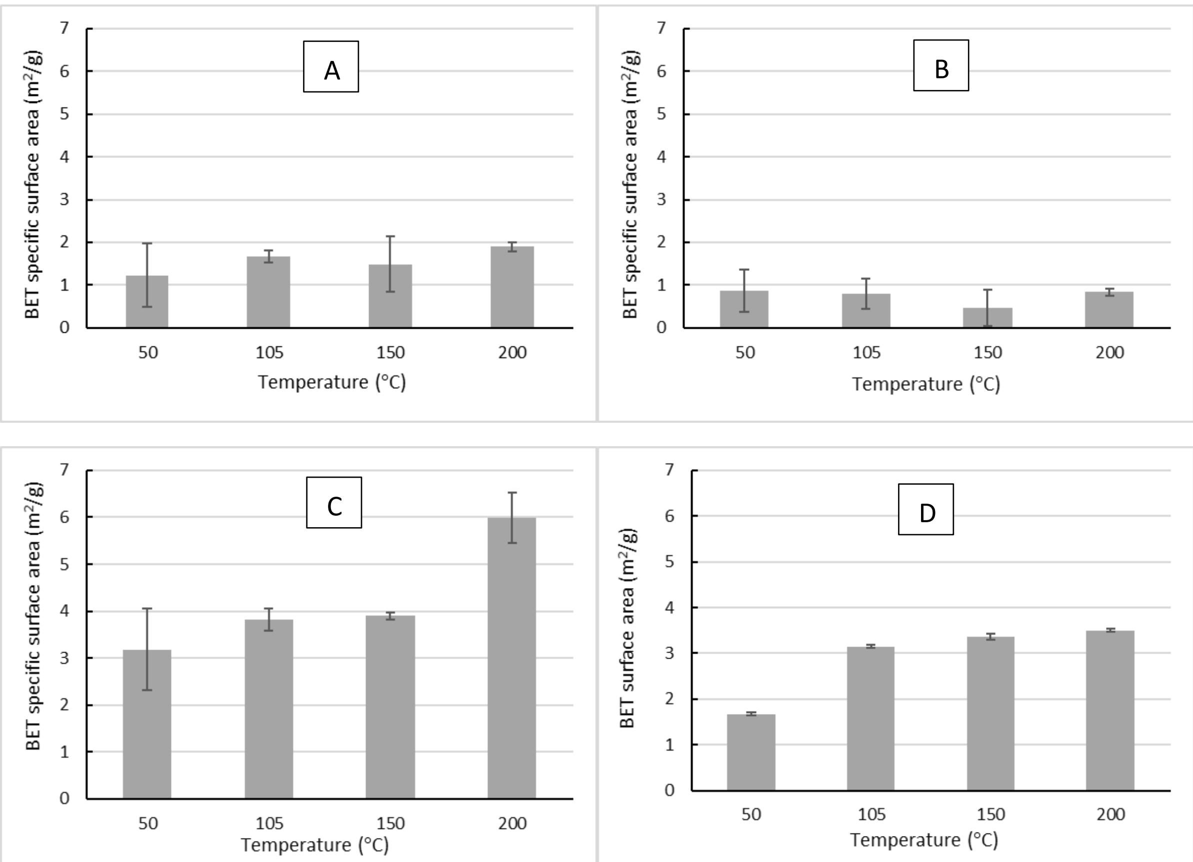
Once the faecal material has turned into a granular solid during drying, the determination of the surface properties can enable a better understanding of the transformation of the faecal material from a slurry to solid. The surface properties can also provide useful information for the characterization of the drying final stage, as well as for the reuse of the dried product.

Experimental procedure

The surface properties were determined for the faecal samples that were dried completely in the oven at 50, 100, 150 and 200°C (experiments performed at UKZN). For this, a BET analyzer *Tristar II Series* was employed to measure the specific surface and mean pore size. The measurement of the pore size was done using two methods, one based on adsorption and the other on desorption.

Results

BET specific surface results



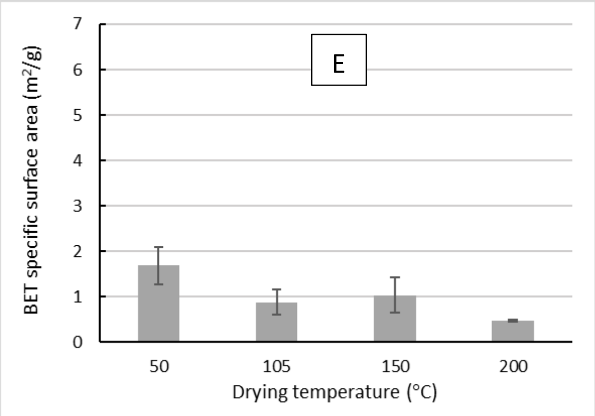


Figure 29. BET specific surface as a function of drying temperature for the samples from ABR (A), UDDT (B), wet VIP (C), dry VIP (D) and fresh faeces

Pore size results

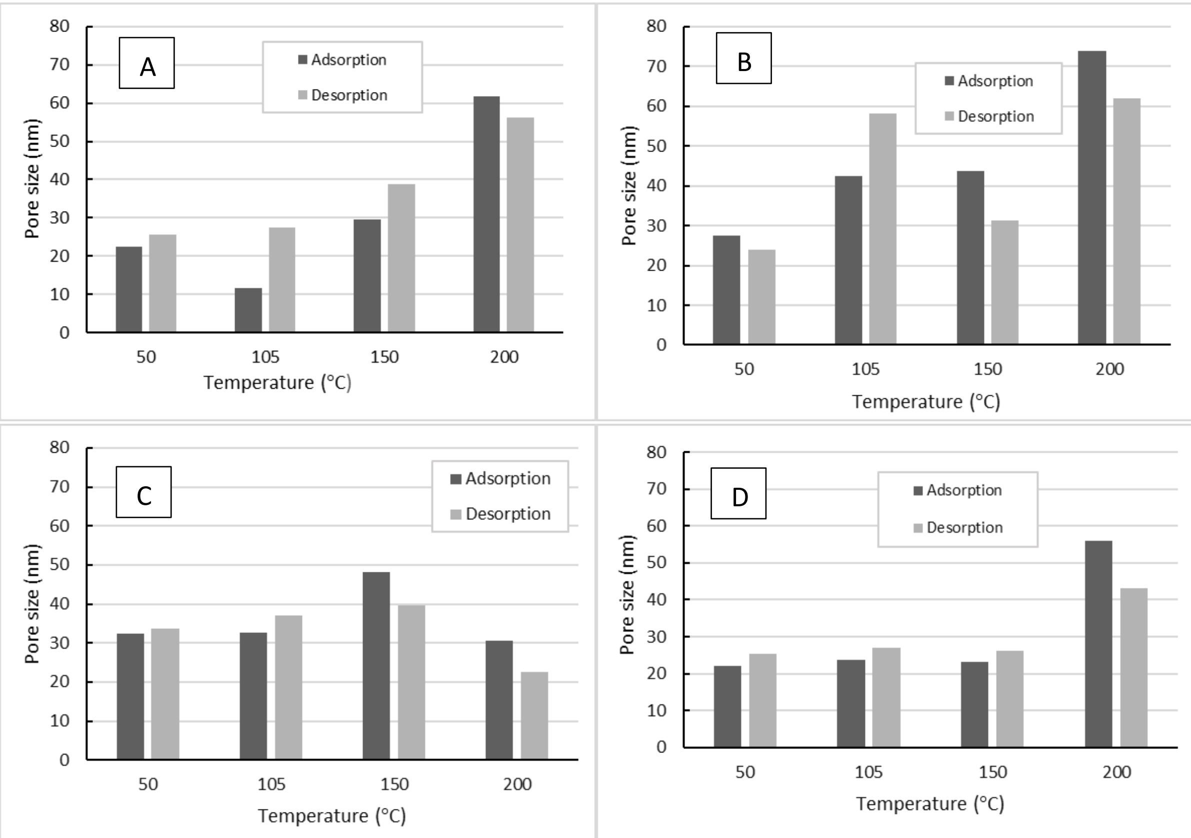


Figure 30. Mean pore size as a function of drying temperature for the samples from ABR (A), UDDT (B), wet VIP (C) and dry VIP (D), using two measurements methods (adsorption / desorption)

Discussion

- It can be observed in Figure 29 that the specific surface was around 1 m^2/g for the ABR, UDDT and fresh faeces samples, and varied between 2 to 6 m^2/g for the wet VIP and dry VIP sludges. These values were relatively low and reflected a solid with low microporosity. No effect of the drying temperature on the specific surface was perceived in any of the cases.

- The mean pore size of the faecal samples ranged mostly between 20 to 50 nm without a clear trend in regards to the type of faecal material and drying temperature (Figure 30). This range of pore size corresponds to mesopores.

Conclusions

- Drying led to a solid with a dominant mesoporous structure with a relative low BET specific surface.
- The drying temperature did not influence the surface properties of the dried solid.

Disinfection performance

Motivation

One of the purposes of drying is the elimination of pathogens organisms that can be a threat to Human health. The pathogens can be deactivated during drying by the heat supplied to the process and the reduction of moisture. The heat can lyse the cells, while the reduction of moisture to low content can lead to an unfavourable environment for the development and survival of the pathogens. It is then important to characterize the disinfection performance of drying as a function of temperature and moisture content.

Experimental procedure

The drying performance was studied by tracking the viability of Ascaris eggs to develop in faecal sludge exposed to different temperatures and dried at different moisture content. Ascaris eggs were selected as the disinfection indicators, as it is known as one of the most resilient pathogens. Therefore, if the Ascaris eggs are deactivated at given treatment conditions, the same could be assumed for the overall of the pathogens. The helminth eggs in this study were from Ascaris Suum, which is a surrogate from Ascaris Lumbricoide but cannot develop in humans. The viability of the Ascaris eggs was determined by counting the number of viable eggs in the microscope. These experiments were conducted at UKZN.

In the first batch of experiments, the Ascaris eggs were exposed to different temperatures (40, 45, 55, 60, 80°C) in water and two different types of faecal sludge (UDDT and wet VIP). The containers with the water and faecal sludge samples were placed in a thermostat bath at a given temperature. After reaching the set temperature, the eggs were spiked in the different mediums and left there during different exposure times. Immediately after this, the water and faecal samples were quenched in an iced water bath, and the eggs were extracted and examined in the microscope to check their viability before and after one month of incubation. This investigation is the continuation of a previous MSc research project where the viability of the Ascaris eggs was determined in water between 60 and 80°C for different exposure times.

In the second batch of experiments, the eggs were spiked in the sludge samples that were dried at different moisture content (60, 50, 40, 30 and 20%wt) and stored for 12 weeks. Each week, the viability of the eggs in each sludge was examined after extracting the eggs from a small amount fo sample. After the 6^{th} week, the faecal samples started to develop a fungi growth, so the results from this point were discarded.

Results

Viability of Ascaris eggs as a function of temperature in water (results from the previous project)

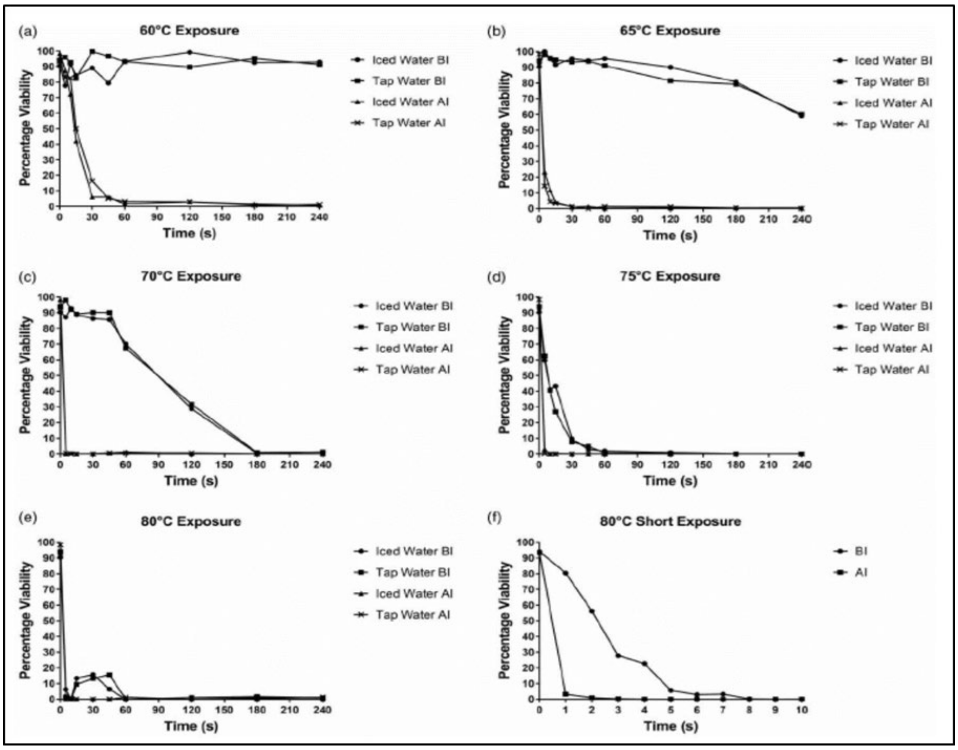


Figure 31. Ascaris eggs viability in water when exposed to 60 - 80°C for different exposure times (BI = before incubation; AI = after incubation). Source: Naidoo, D., Appleton, C. C., Archer, C. E., & Foutch, G. L. (2019). The inactivation of Ascaris suum eggs by short exposure to high temperatures. Journal of Water, Sanitation and Hygiene for Development, 9(1), 19-27.

Viability of Ascaris eggs as a function of temperature in water

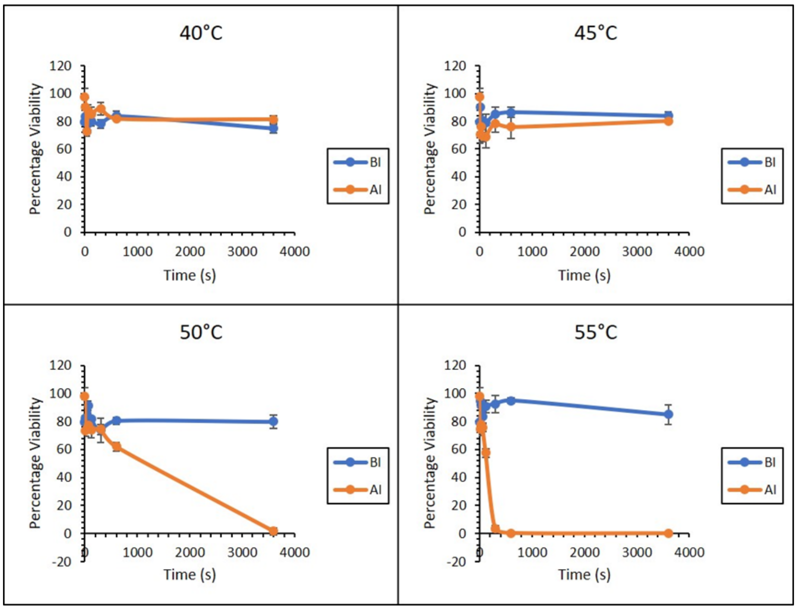


Figure 32. Ascaris eggs viability in water when exposed to 40 - 55°C for different exposure times (BI = before incubation; AI = after incubation)

Viability of Ascaris eggs as a function of temperature in water and the faecal sludge samples

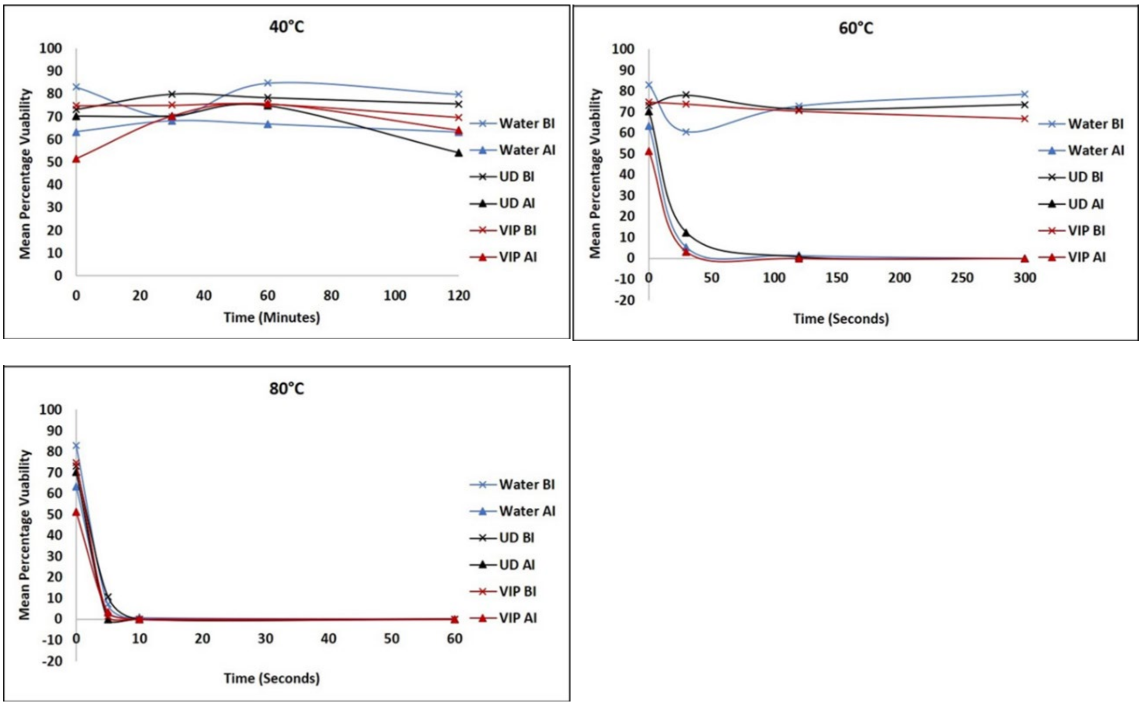


Figure 33. Ascaris eggs viability in water, wet VIP and UDDT sludge when exposed to 40 - 55°C for different exposure times (BI = before incubation; AI = after incubation). Note that "UD" in the legend is equal to "UDDT".

Viability of Ascaris eggs as a function of moisture content in the faecal sludge samples

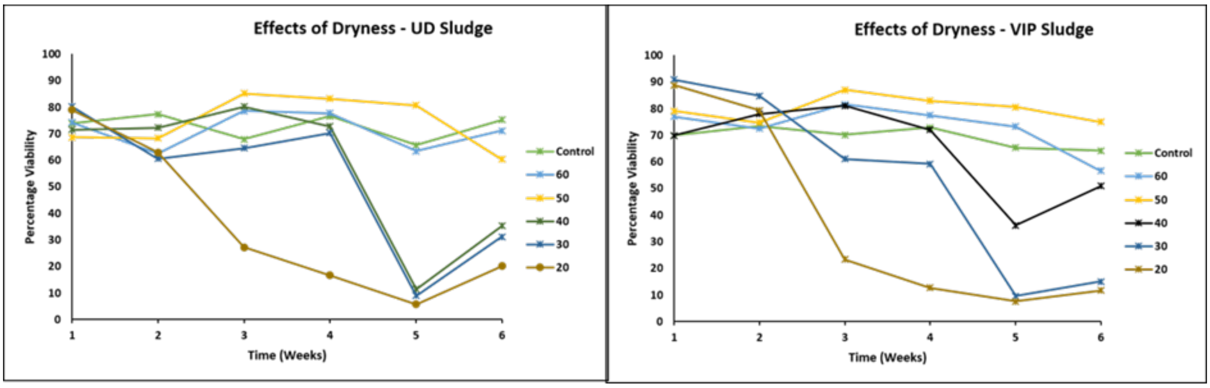


Figure 34. Ascaris eggs viability in the UDDT and VIP sludge dried at different moisture content (20, 30, 40, 50, 60%wt) as a function of the storage time

Discussions

- As it can be seen in Figure 33, the viability results were similar between the water and the sludge samples at the different testing temperatures, which means that the medium on which the Ascaris eggs were deposited did not influence their deactivation. Therefore, water can be used to study the effect of temperature on the deactivation of Ascaris eggs, which will reduce the biological risks associated with the use of real faecal matter. The results obtained with only water in Figure 31 and Figure 32 can then be applied to faecal sludge.

- The viability of Ascaris eggs was reduced by increasing the temperature (Figure 31 and Figure 32). It can also be noted that there was a difference between the results before and after incubation. In fact, some of the eggs looked healthy before incubation, but they did not develop after incubation, which demonstrated that they were fatally damaged during the heat treatment even if their initial aspect did not reflect this damage. The difference between the results before and after incubation was larger as the treatment temperature was lower. This said, it is more pertinent to study the deactivation of the Ascaris eggs based on the viability results after incubation.
- Taking into account only the results after incubation, the viability of the eggs started to decline from 50°C and decreased exponentially by increasing the temperature. While the time for a total inactivation of the Ascaris eggs took several hours to occur at 50°C, the eggs were inactivated in less than 1 minute above 60°C and a few seconds above 70°C.
- The viability of the Ascaris eggs was also affected by the level of dryness of the sludge. As it can be observed in Figure 34, the viability of the eggs declined from the 4^{th} week at a moisture content of 30 and 40%wt, and from the beginning of the storage at 20%wt. Hence, lower moisture content favoured a sooner Ascaris eggs inactivation.

Conclusions

- The high temperature and low moisture content enabled to reduce the viability of Ascaris eggs.
- The effect of temperature was considerably faster than that from moisture content. The sludge could be disinfected in a few seconds by exposing it to temperatures higher than 60°C. In contrast, the sludge disinfection could occur after several weeks by reducing the moisture content below 40%wt.

Effect of viscous heating on faecal sludge drying

Motivation

The viscous heating is a disinfection process where the sludge is heated through the frictional forces provoked by the forced convection of sludge in a small volume. The high shearing of the sludge during this process could potentially damage the solid structure by breaking flocs, polymers, cells structure and interparticle bonds. These actions could release moisture that was trapped or bounded within the solid matrix, making it easier for its removal through dewatering and drying.

Experimental procedure

Faecal sludge from UDDT was treated in a large-scale viscous heater located at the faecal sludge treatment plant at Isipingo, South Africa. The treatment capacity of the viscous heater is 1,000 L/h, and it operates at 2.5 bar. A photograph of the viscous heater is depicted in Figure 35.

Figure 35. Photograph of the 1,000 L/h viscous heater

In this process, the sludge was exposed to 96°C for 3 and 5 min, 102°C for 30 min and 105°C for 6 minutes. The effect of the viscous heater on faecal sludge drying was assessed by comparing various properties between the sample before and after treatment, among which the drying kinetics, water activity, moisture content, chemical composition (carbon, nitrogen, sulphur), and particle size distribution. These experiments were conducted at UKZN.

The drying kinetics were measured in a moisture analyzer *Radwag Max 50* at 105°C. The water activity was analyzed in the *AquaLab Tunable Diode Laser-TDL* analyzer. The moisture content was measured using the Standard Method for the Examination of Water and Wastewater. The carbon, nitrogen and sulphur content were determined through the CNS analyzer *LECO TrueMac.* The particle size distribution was characterized using the *Malvern Mastersizer 3000* instrument.

Results

Moisture content and water activity results

Table 6. Moisture content and water activity measured for the UDDT faecal sludge before and after viscous heating treatment at different time-temperature exposures

SLUDGE TYPE	MOISTURE CONTENT (%)	WATER ACTIVITY
Untreated UDDT Sludge	68.17 ± 0.07	0.9603 ± 0.008
VH-Treated UDDT Sludge at 96°C	63.18 ± 0.29	0.9693 ± 0.0034
VH-Treated UDDT Sludge at 102°C	58.2± 0.3	0.9652 ± 0.007
VH-Treated UDDT Sludge at 105°C	62.47 ± 0.35	0.9604 ± 0.0049

Drying kinetics results

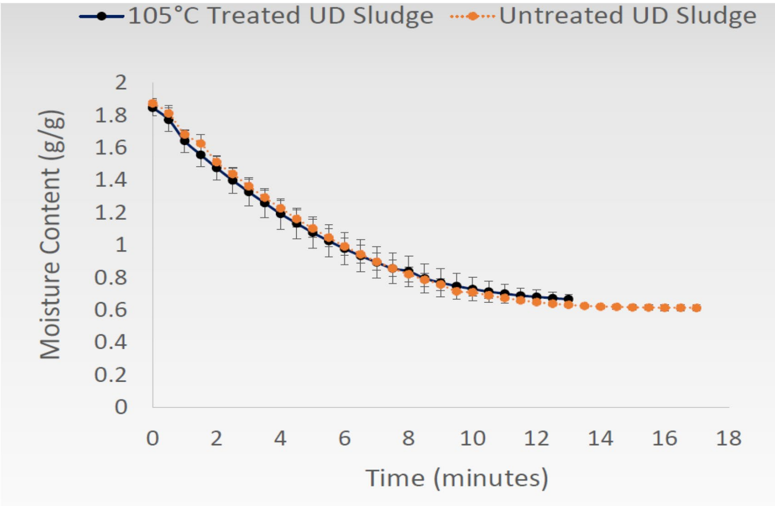


Figure 36. Moisture content versus time during the drying of the UDDT faecal sludge before and after viscous heating treatment at 105°C

CNS results

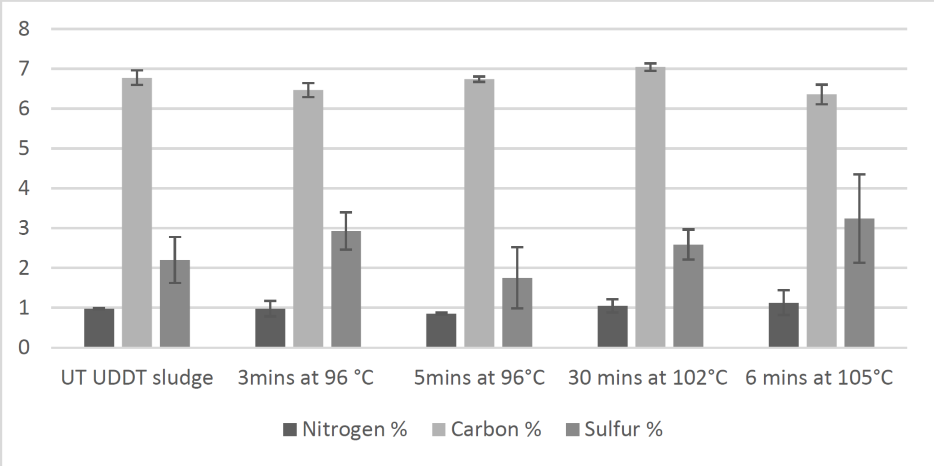


Figure 37. Carbon, nitrogen and sulphur content the UDDT faecal sludge before and after viscous heating treatment at different time-temperature exposures

Particle size distribution results

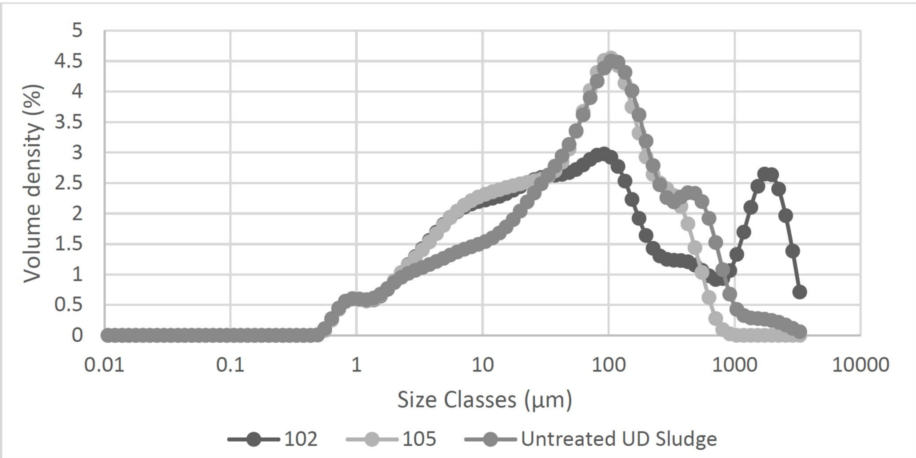


Figure 38. Particle size distribution of the UDDT faecal sludge before and after viscous heating treatment at different time-temperature exposures

Discussion

- As seen in Table 6, the viscous heating treatment reduced the moisture content of the sludge. The loss of moisture probably occurred after the heated sludge exited the viscous heater and was exposed to the environment, causing the evaporation of the moisture from the heat gained during the process. In contrast, the viscous heater did not affect the water activity, suggesting that the boundedness of moisture in the sludge was not altered.
- The drying kinetics of the sludge remained the same before and after treatment (Figure 36), showing that the viscous heater did not have any impact on the drying kinetics.
- The viscous heating did not lead to any significant variation of the carbon, nitrogen and sulphur content (Figure 37), as well as the particle size distribution (Figure 38). Therefore, this process did not cause a degradation of the solid material or damage to the floc structure.

Conclusion

- The heat produced during the process enabled to evaporate part of the sludge moisture content.
- The viscous heating did not induce enough structural changes to destroy the floc structure and increase the amount of unbound water. Therefore, it did not lead to an improvement in the drying rate, as initially hypothesized.

Effect of ageing on the drying of fresh faeces

Motivation

In the innovative sanitation technologies, such as the reinvented toilets, the excreta waste is treated in-situ. Some of the technologies rely on the separation of the liquid and solid stream from the toilets. In these technologies, the faecal stream usually passes through subsequent stages of dewatering, dried and combustion. However, the treatment of the faecal fraction is not instantaneous. Indeed, there is a holding time on which the faecal waste is retained before its treatment. During this period, the faecal fraction can be degraded through biochemical reactions from the microbial populations contained originally from the faeces or obtained from contamination. Fresh faecal waste is not stabilized, and thus it can offer an environment rich in nutrients for the development of microorganisms.

The degradation of the faecal fraction can lead to the release of moisture that was bounded or trapped inside the solid matrix, facilitating its removal through dewatering or drying.

Experimental procedure

The effect of ageing on drying was studied for fresh faeces during one month, which was deemed as the maximal time that the faecal waste could be realistically held before its treatment in innovative toilet technology. Fresh faeces were stored at ambient conditions and analyzed at different time intervals for one month. The performed analyses were as follow:

- Drying kinetics measured in a moisture analyzer *Radwag Max 50* at 105°C;
- Water activity analyzed in the *AquaLab Tunable Diode Laser-TDL* instrument;
- Moisture and volatile solids content measured using the Standard Methods for the Examination of Water and Wastewater;
- Carbon, nitrogen and sulphur content measured through the CNS analyzer *LECO TrueMac;*
- Rheological characteristics determined in a *Anton Paar MCR 51* rheometer.
- Particle size distribution characterized using the *Malvern Mastersizer 3000* instrument.

These experiments were conducted at UKZN.

Results

Moisture content and water activity results

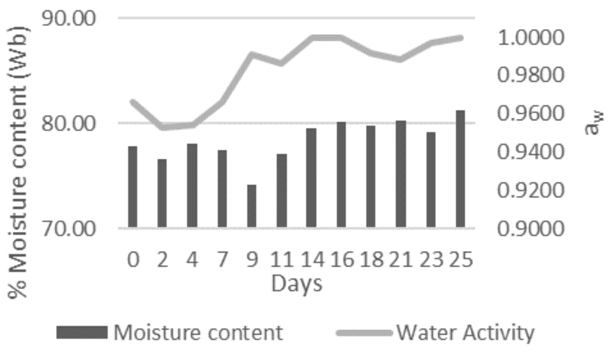


Figure 39. Moisture content and water activity measured in the faeces at different ageing times

Drying kinetics results

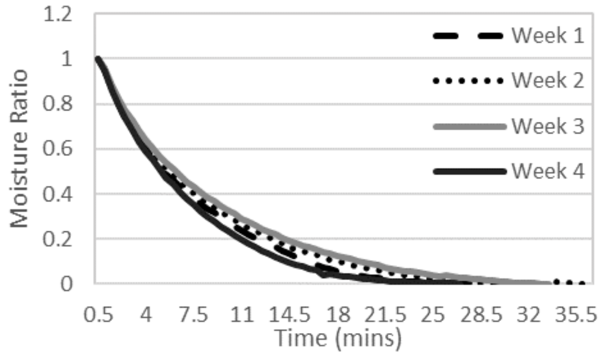


Figure 40. Moisture ratio versus time measured in the faeces at different ageing times (moisture ratio being as the moisture content normalized by its initial value)

Rheology results

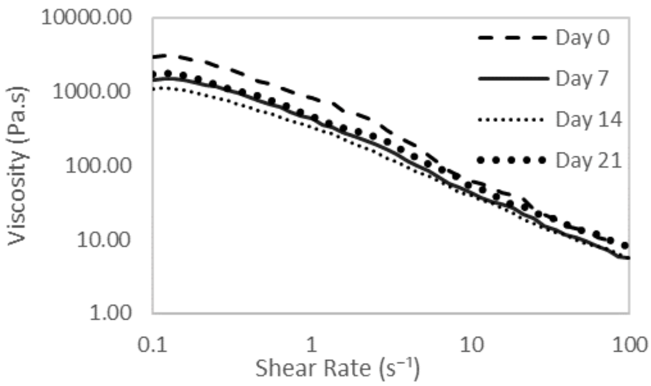


Figure 41. Viscosity versus shear rate measured in the faeces at different ageing times

Carbon and volatile solids result

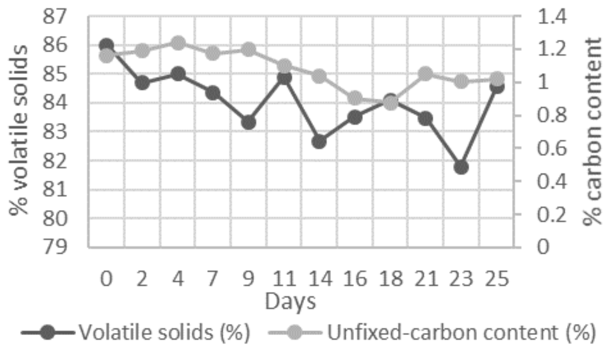


Figure 42. Carbon and volatile solids content measured in the faeces at different ageing times

Particle size distribution results

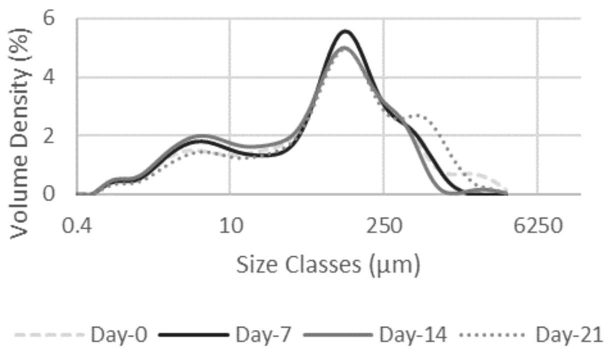


Figure 43. Particle size distribution measured in the faeces at different ageing times

Discussion

- The water activity and moisture content increased slightly during the storage time (Figure 39), whereas the carbon and volatile solids contents declined slightly (Figure 42). These results could have arisen from the degradation of the faeces, which reduced the organic matter (explaining the decrease of the carbon and volatile solids contents) and produced unbound water (explaining the increase of the moisture content and water activity).
- During the tests, the growth of maggots was noticed in the faeces, which was probably the main reason for the degradation of the faecal matter. Indeed, further experiments were performed for another project where the development of maggots was avoided by placing a fine mesh above the container with the faeces. In these experiments, a completely different behaviour was observed, in which the faecal matter was dehydrated with time and did not undergo any degradation.
- The ageing of the fresh faeces did not bring any significant effect on the drying kinetics (Figure 40), rheological properties (Figure 41) and particle size distribution (Figure 43). These results signify that the degradation of the faecal matter, assumed in the previous paragraph, did not change the bulk structure of the material nor improve the drying of the sample.

Conclusions

- Ageing of the fresh faeces led to a slight degradation of the faeces, probably due to the development of maggots.
- However, this degradation did not affect the bulk structure of the faeces and consequently did not have any impact on drying, as initially hypothesized.

Qualitative observations

Motivation

Interesting information about the drying process can be obtained from visual observations.

Experimental procedure

During the oven drying experiments at UKZN, it was asked to the experimenters to note and record their visual observations and perceptions.

Results

Faecal sludge samples aspects after oven drying

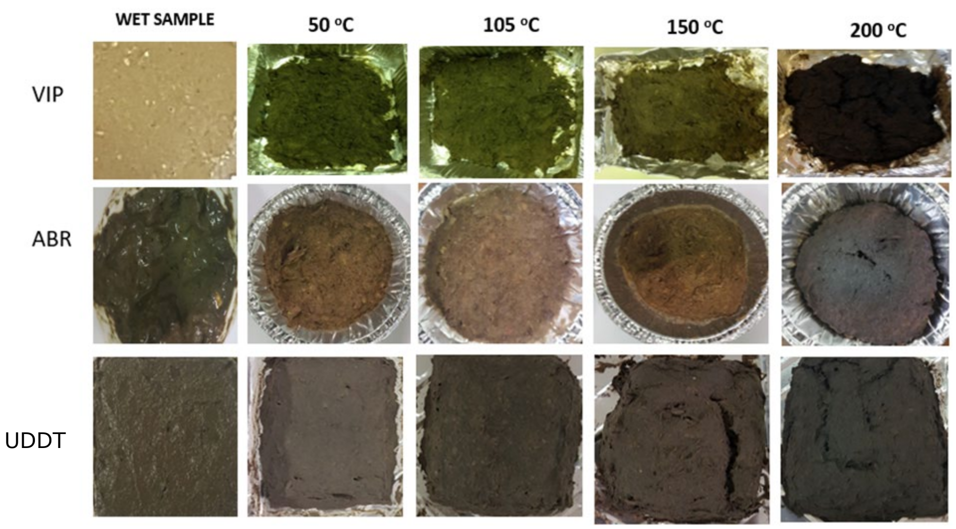


Figure 44.Photographs of ABR, UDDT and wet VIP samples dried in the oven at different temperatures

Observations during drying of fresh faeces

Table 7. Observations of the experimenter during the drying of fresh faeces in the oven

Moisture content	Smell	Crust	Colour	Surface	Consistency
80-70%	Heated faeces smells more pungent in the first hour.	Thin film of crust formed	Film is a darker brown due to oxidation. The inside is lighter in colour and retains the yellow colour of fresh faeces.	The thin film forms on top sealing in the rest of the sample. The surface smoothens out under heat. The sample slightly rises or spreads under heat	The crust forms is thin like the skin of cream on milk. At 200°C the skin was drier and crustier compared to 50°C and 105°C
70-60%	The odour resembles that of a butchery which is concentrated	Thin film of crust formed. Thicker film than the one observed above. If left without stirring cracks appear on the crust surface.	The crust is a darker greenish brown but the faeces underneath has more yellow tinge to it.	Sample is drying from the edges. Since drying is carried out with mixing every 20 minutes, the surface is uneven.	The sample is sticky and clings together and to the surface of the container.

60-40%	The odour is sweeter	As the moisture decreases to 40%, the sample becomes grainier, and paste like. The tips of the particles and the edges are drier than the centres, which is periodically corrected by mixing.	The faeces colour changes to darker brown throughout	Surface has a thicker crust and the thin edges tend to be drier than the rest if left unattended	The samples are clay like with visible paste like consistency.
40-20%	The odour is sweet	The consistency becomes grainier and the faeces dries in bigger pieces trapping the moisture inside. The consistency is like a thick toffee, harder outside than inside	Colour remains dark brown	The surface of faeces with 20% is heavily crusted. Faeces dries in clumps.	Larger particle sizes with a drier crust.
20-0%	There is no pungent or predominant odour	At nearing 0% the faecal sample is brittle and crisp. Sample dried in clumps are harder to break down.	The dark brown has slightly ashy/grey tinge to it	The surface is hard and brittle.	Hard consistency.

Discussions

- The odours perceived by the experimenters changed from unpleasant to pleasant across the process, to finish with the absence of any smell at the end of the process (Table 7).
- A crust tended to appear at the surface of the faecal matter, obliging to the experimenter to stir the material continuously to avoid a non-homogenous drying (Table 7).
- The faecal matter changed of colour as it was dried (Figure 44).
- The change of consistency from a slurry to a solid occurred between 60 to 40%wt moisture content (Table 7).

Conclusions

- Drying led to the removal of odours, change of colour and crust formation of the faecal material. Crust formation can provoke a non-homogenous drying, so it should be avoided as possible.
- The transition of faecal material from a paste to a solid occurred between 60 and 40%wt moisture content.

General discussion

- Temperature showed to be a very important factor during the drying process as it influenced the moisture removal and disinfection rate greatly. A drying temperature above 70°C was high enough for a fast Ascaris eggs deactivation of a few seconds. In terms of moisture removal, a temperature comprised between 100 and 150°C seemed to be ideal. Below 100°C, the drying process occurred relatively slowly, while above 150°C the increase of the drying kinetics was too little to justify the additional heat input (which can result in higher operating costs). Moreover, drying above 200°C can cause the thermal degradation of the faecal material, which could decrease the quality of the dried product for its reuse.
- The fresh faeces samples tended to dry slower than the faecal sludge samples at temperatures below 100°C, which could be due to a slightly higher level of boundedness of moisture within the material. Even though this assumption could not be verified through the water activity or heat of drying measurements, the centrifugation tests suggested a higher level of moisture boundedness for faeces as no unbound water was observed in this case, on the opposite to the faecal sludge samples. Above 100°C, none difference of drying kinetics could longer be observed, and all the samples dried at approximately the same rate. This result entails that the influence of moisture boundedness on drying kinetics disappeared at high temperatures, where drying proceeded at a fast rate for all samples.
- The faecal material could be dried to low moisture content even at a high relative humidity atmosphere. It was also demonstrated that the dried faecal matter was a hygroscopic material that could be remoisturized if exposed to humid air. This property needs to be considered for the storage of the dried faecal matter before its reuse. A gain of humidity can increase its weight and potentially reactivate certain pathogens.
- The heat of drying was fairly constant during the process, except at the final stage from where it increased drastically. This steep corresponded approximately to the point where the water activity started to drop for most of the samples. These results imply that the remaining moisture in the faecal material was strongly bonded to the solid matrix and would require a considerably higher amount of energy for if removal. Therefore, drying could be stopped before this point to reduce the energy consumption of the process.
- The heat required to dry the faecal samples, varying mostly between 3,000 and 5,000 kJ/kg, was generally higher than the latent heat of pure water vaporization. This result highlights that the faecal samples presented a certain level of moisture boundedness, which was corroborated by water activity values comprised between 0.9 and 1 during the major part of the drying process (from the initial moisture content until 30%wt). Not a clear trend as a function of the type of faecal sample and drying temperature could be observed for the heat of drying.
- The consistency of the faecal samples was dependant on the moisture content. The samples with a moisture content higher than 90%wt exhibited a liquid consistency, while the samples with a moisture content around 70 – 80%wt presented a semi-solid aspect with a paste consistency. Between approximately 40 and 60%wt moisture content, the samples transitioned from a paste to solid consistency. Below 40%wt moisture content, the faecal matter became mostly solid. During the transformation of the faecal material from its initial aspect to a solid, the water activity remained quite constant, which means that the faecal material presented the same moisture boundedness during this process. It is after that the faecal samples became solid that the water activity started to drop, which occurred from

approximately 30%wt moisture content. This result entails a high level of moisture boundedness after the faecal material has been turned into a solid.

- The faecal material could be dewatered at the most up to 60 – 70%wt moisture content through centrifugation. As expected, the sludges with liquid consistency tended to be dewatered at a higher extent compared to the semi-solid samples, surely because of a higher amount of unbound or loosely bound moisture. The fresh faeces could not be dewatered, suggesting the absence of unbound moisture in this type of material.
- The thermal properties in the undried faecal samples were highly influenced by its moisture so that their values were close to those from pure water. This influence became less important as the drying of the material proceeded and ceased below approximately 40%wt moisture content from where the thermal properties remained content after further drying. Around this moisture content, it was observed that the faecal material turned from a pasty consistency to a granular solid, which could be related to the fact that the thermal properties stopped to vary from this point after further moisture removal. It can be noted that the loss of the moisture influence on the thermal properties happened after the faecal material has become solid.
- The reduction of moisture content below 40%wt led to the deactivation of Ascaris eggs (likewise after the sludge has turned into a solid). At 40%wt moisture content, the water activity varied between 0.9 and 1.0, showing a certain level of boundedness of moisture in the sludge, and was close to reaching the point from which the water activity started to drop (20 – 30%wt moisture content). This level of moisture boundedness was unfavourable for the development of Ascaris eggs.
- According to the water activity tables in the food industry, most of the pathogenic bacteria, , including Escherichia Coli, Salmonella, Shigella and Vibrio Cholerae, are deactivated below a water activity of 0.91, corresponding to a moisture content of 20 - 30%wt in this study. Thereby, drying the faecal materials below this threshold would guarantee to deactivate most pathogenic bacteria and Ascaris eggs. Some microorganisms survive to water activities below 0.90, such as Halophilic bacteria, yeasts and fungi, but they do not represent a considerable threat for humans.
- Drying caused a change of colour, crust formation and released the molecules responsible for odours. After drying, the dried material was odourless. The crust formation at the surface can limit the removal of moisture underneath it, leading to a heterogenous drying. It must be then mitigated for achieving an efficient drying process.
- Drying led to the formation of a solid with a relative low BET specific surface and pore size comprised in the range of mesopores.
- The faecal samples present a good absorbance of approximately 0.6 – 0.7 in the wavelength range of 350 to 2,200 nm, which could be favourable for solar and NIR drying processes.
- The stirring of faecal sludge or ageing of fresh faeces did not improve the drying under the explored conditions, as it could be assumed initially.

General conclusions/takeaways

- The optimal temperature to dry is situated between 100 and 150°C, where the highest drying rate could be obtained at the minimal heat input. These conditions should also ensure pathogens deactivation. Drying temperature should not exceed 200°C if thermal degradation wants to be avoided.
- It is possible to dry the faecal matter to low moisture content at high relative humidities. This behaviour is positive for the drying processes, particularly those conducted at low temperature (i.e. at ambient or a little higher temperature), such as the drying beds.
- The faecal material presents a relatively good absorbance of solar and NIR radiations. Therefore, solar and infrared drying represent potentially viable methods to dry faecal waste.
- Above a moisture content of 60 - 70%wt, the faecal matter is found as a suspension (liquid consistency) or semi-solid (paste consistency) that can be dewatered through mechanical means, indicating the presence of unbound or loosely bound moisture. Evidently, dewatering is more important when the faecal material has a more liquid consistency because of a higher amount of unbound moisture. The thermal properties of faecal matter as suspension or semi-solid are controlled by their moisture content.
- Between a moisture content of 40 to 60%wt, the faecal material turns from a paste to solid consistency, it cannot be dewatered anymore, and the influence of the remaining moisture on its thermal properties diminishes.
- Below a moisture content of 40%wt, the faecal matter becomes a solid with a mesoporous structure. At this stage, the thermal properties are not influenced anymore by the moisture content. Drying below approximately 30%wt would require considerably higher energy input because the remaining moisture is tightly bonded to the matrix solid. Drying could be then stopped at this point, which would enable to lead to energy savings. Besides, this level of moisture content is low enough to limit the development of pathogens.
- The dried faecal matter is hygroscopic, so it can be moisturized after drying during its storage. It should be the avoided to store the faecal matter under high humidity conditions, as the regain of moisture could cause an increase of the weight of the material and open the possibility of reinfection with pathogens or mould.
- Fresh faeces tend to be more difficult to dry than faecal sludge at low drying temperature (<100°C), probably to slightly higher moisture boundedness. At high drying temperature (>100°C), the effect of the moisture boundedness fades, and faeces and faecal sludge dry at the same rate.
- The heat of drying is significantly higher than the latent heat of water vaporization for all type of faecal matter, except for liquid sludge with a moisture content close to 100%wt. Therefore, the moisture in faecal matter, except when it is very diluted, exhibits a certain degree of boundedness with the solid structure.
- Crust formation can appear during drying. In the extent of the possible, measures have to be implemented to reduce or avoid crust formation that can cause an efficient drying.
- Drying of faecal matter comes along with the release of odours during the process, probably due to the volatilization of the olfactory compounds. No odours can be perceived at the end of the process, probably because all the olfactory compounds have been volatilised. The final product is odourless. The drying process must consider measures to mitigate odours.
- It is difficult to modify the moisture boundedness of the faecal material, thus to influence its ability of dewatering or drying, through mechanical means or storage.