UNIVERSITY OF KWAZULU-NATAL

INYUVESI YAKWAZULU-NATALI

DRYING OF FAECAL SLUDGE FROM VENTILATED-IMPROVED PIT LATRINES (VIP LATRINES) USING SOLAR THERMAL ENERGY

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Chemical Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard College campus, South Africa. The research was financially supported by the Water Research Commission (WRC).

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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I, …………………………………………………………………… , declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original work.

2. This dissertation has not been submitted for examination or degree at any other university.

3. This dissertation does not contain other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons.

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5. This dissertation does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the thesis and in the references sections.

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DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

1. Mugauri TR*, Inambao F, Septien S, Singh A 2017. Exploration of the use of solar thermal energy for faecal sludge drying. Paper presented at the Botswana Institution of Engineers Conference, 17th to 19th October 2017, Gaborone, Botswana. (Article available in proceedings).

2. Mugauri TR*, Septien S, Inambao F, Singh A 2017. Solar drying and pasteurization of faecal sludge. Paper presented at the annual College of Agriculture, Engineering and Science Postgraduate Research Day, 28th October 2017, Durban, South Africa. Presented by TR Mugauri. (Article available in proceedings).

3. Mugauri TR*, Septien S, Inambao F, Singh A 2017. Exploration of the use of solar thermal energy for faecal sludge drying. Paper presented at the 8th International Young Water Professionals (IYWP) Conference, 10th to 13th December 2017, Cape Town, South Africa. Presented by TR Mugauri. (Article available in proceedings).

4. Septien S, Mugauri TR*, Inambao F, Singh A 2018. Solar drying of faecal sludge from on-site sanitation facilities. Paper presentation at the 5th Southern Africa Solar Energy Conference (SASEC), 25th to 27th June 2018, Durban, South Africa. Presented by S Septien.

5. Septien S, Mugauri TR*, Inambao F, Singh A 2018. Use of solar thermal energy for the drying of faecal sludge. Paper presentation at the Water Institute of South Africa (WISA) Congress, 24th to 27th June 2018, Cape Town, South Africa.

6. Septien S, Mugauri TR*, Inambao F, Singh A 2018. Solar drying of faecal sludge from pit latrines in a bench-scale device. Paper presentation at the 41st Water, Engineering and Development Centre (WEDC) International Conference, 9th to 13th July 2018, Nakuru, Kenya.

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ABSTRACT

Ventilated improved pit (VIP) latrines are a basic form of sanitation in South Africa. The main challenge facing the application of VIP latrines is the gradual fill up of the pit due to usage. A sustainable way of treating FS remains from sanitation systems is by using solar energy. This project is focused on the characterisation of solar drying for FS treatment.

A solar thermobalance was designed and constructed to investigate the solar and open-air sun drying of FS. Mass variations, temperature, humidity and solar irradiance properties were monitored during the drying process. The drying experiments for solar drying were conducted with the following variables: weather conditions; air temperature; airflow velocity; sample thickness and surface area. The experiments were carried out in October and November 2017.

The drying kinetics were observed to be influenced by the weather conditions, air temperature and air flow rate, but the sample thickness and surface area of the sample did not have any significant effect on the drying rate, under the explored conditions. Solar drying recorded drying rates which averaged 0.892 kg/h.m^2 across the investigated parameters and were comprised between 0.622 to 1.135 kg/h.m^2, whereas open-air drying averaged a drying rate of 0.479 kg/h.m^2, varying in the range 0.686 - 0.078 kg/h.m^2. The faecal sludge was found to dry best under sunny conditions, 30 $^{\circ}$C air temperature and 0.5 m/s air flowrate.

Qualitative and quantitative analysis was also conducted to characterise the influence of solar and open-air sun drying on the physico-chemical characteristics of faecal sludge. Density, shrinkage, thermal conductivity and heat capacity showed great dependence on the final moisture content which depended on the employed drying conditions. Crusting and cracking of the samples were observed to occur, and their intensity depended on the investigated conditions and were suspected to affect the drying rate in specific experimental conditions. This is shown in the lower drying rates for 1.0 m/s air flow rate and 60 $^{\circ}$C air temperature. Odour strength increased with lower final moisture content.

In summary, the application of solar energy for drying proved to be a feasible option for the treatment of FS. Drying in a solar thermal system with controlled conditions of air properties will consist in an improvement on the current sludge dehydration practices, such as the drying beds (open-air drying).

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CHAPTER 1: INTRODUCTION

This section looks into the background of the study, covers the aim, scope, general and specific objectives of the research and an outline of the dissertation.

1.1 Background of the study

At the independence of the Republic of South Africa, according to a report by the Department of Water Affairs (2012), more than 20 million people (more than 50 % of the population of the state) did not have access to basic sanitation. This was due to the lack of development during the apartheid era (Mnisi 2011). According to the United Nations Development Goals and Sustainable Development Goals (SDGs), access to water and basic sanitation have been declared as basic human rights (Corcoran 2010; Sachs 2012).

Over the years, governments and organisations have moved to make provision for sanitation systems through standardised policies and guidelines (Still, Foxon et al. 2012). Though there has been an improvement in access to sanitation, the joint monitoring programme implemented for water supply and sanitation estimated that internationally in 2015 approximately 2.5 billion people did not have access to improved sanitation systems and resorted to the use of primitive sanitation systems and open defecation, the greater population being reported in Asia and sub-Saharan Africa (two-thirds and a quarter respectively) (Winker, Vinnerås et al. 2009; Freeman, Ogden et al. 2013; Udert, Buckley et al. 2015; WHO 2015) .

Improved sanitation systems are classified in terms of storage of waste material, being described as either off-site or on-site sanitation systems. Off-site sanitation systems are systems in which the faecal sludge is collected from the individual sanitation systems and carried away from the site to be treated and disposed of. On-site sanitation systems are sanitation systems in which the safe disposal of FS takes place on or near the site of the toilet. On-site sanitation systems include ventilated improved pit latrines (VIP latrines), septic tanks and urine diversion (UD) toilets. These kinds of sanitation systems are the most commonly used across the world (Austin and Van Vuuren 2001; Langergraber and Muellegger 2005; Mnisi 2011; Bakare, Foxon et al. 2012). Sanitation systems can also be classified based on water usage and/or single or communal use.

VIP latrines are an improvement on basic latrine systems because of the introduction of a vent pipe fitted with a fly screen at the top to assist in the reduction of odours and trapping of insects from entering and/or leaving the latrine (Buckley, Foxon et al. 2008; Still, Foxon et al. 2012). These latrines provide the basic requirements for improved sanitation and have been the basic standard of sanitation provision in South Africa. As a result, the eThekwini municipality has provided over 60 000 VIP latrines since 1999 (Brouckaert, Foxon et al. 2013). As with all on-site sanitation systems, due to usage VIP latrines fill-up, it was reported that by 2009, 10 years later, 35 000 latrines were full and were emptied by the municipality (Still, Foxon et al. 2012).

Due to the nature and volume of faecal sludge from VIP latrines, there are difficulties in its safe disposal (Still, Foxon et al. 2012). Initial disposal options were the use of disposal in trenches or into wastewater treatment plants (WWTP) (Arlabosse, Chavez et al. 2004; O'Riordan 2009; Rose, Parker et al. 2015). This proved to be hazardous to the environment as the sludge was disposed of untreated and resulted in shock loading of wastewater treatment plants, respectively. As with animal excreta, faecal sludge has significant valorisation potential, it contains most of the nutrients needed for crop production and soil rejuvenation. These can be recycled through treatment systems and be used to reduce the use of non-renewable chemicals in chemical fertilisers (Malkki 1999; Sharma Sunil 2013; Rose, Parker et al. 2015). Other potential uses of FS include the production of biogas, and as animal feed, with ongoing research into the application of FS as a fuel (Langergraber and Muellegger 2005; Fytili and Zabaniotou 2008; Muspratt, Nakato et al. 2014; Rose, Parker et al. 2015).

A number of treatment systems have focussed on the safe disposal of FS, including the use of drying beds and the black solder fly. The eThekwini municipality resorted to the use of the latrine dehydration and pasteurization machine (LaDePa) which produces dried and pasteurised pellets from the FS which can be utilised as a fertiliser and soil conditioner.

Drying is the removal of moisture from a substance, which allows for a significant reduction in the mass and volume of the substance, resulting in the reduction in costs associated with packaging, storage and transportation (Okos, Narasimhan et al. 1992). Examples of conventional drying techniques include mechanical dewatering, freeze drying, radiative drying and hot air convective drying, but these are expensive and energy intensive with most of them dependent on unrenewable sources of energy.

The United Nations Development Program (2000), Goldemberg (2000) and Banerjee (2005) reported that 80% of the world's total energy requirements emanate from fossil fuels with renewable energy sources accounting for only 2 % to 3 %, highlighting the need for a transition to renewable energy systems. Over 40 % of industrial use of energy is directed towards heating applications.

Drying of moist materials involves simultaneous heat and mass transfer phenomena, which take place inside the material being dried, as a result making it a complex process (Perumal 2007). Drying kinetics are affected by humidity, air temperature, size of material and air flow rates (Kiranoudis, Maroulis et al. 1992, Kamwere 2017).

Solar thermal energy is a renewable energy option with vast potential due to its abundance, inexhaustibility and non-polluting nature (Basunia and Abe 2001). The gradual reduction in the costs of solar collectors coupled with the increase in environmental pollution concerns and increase in costs of fossil fuels, have resulted in the increase of the feasibility studies of solar drying. Solar drying refers to the use of solar thermal energy for drying operations in controlled conditions with the application of scientific data whereas sun drying refers to the uncontrolled use of direct sunlight for drying. A variety of solar drying technologies have been used for various applications, such as greenhouse, box and tent designs (Mühlbauer Esper et al.). These differ due to the variation in solar intensities experienced in different locations (Bahnasawy and Shenana 2004).

Solar dryers have acquired a high footprint in the drying of biological products, mainly agricultural produce, as they provide protection of the substance from the environment, and provide a controlled environment which results in higher drying rates compared to sun drying technologies in which the environment is not controlled (Hossain and Bala 2002). Solar dryers are cost efficient because they use simple designs and are relatively cheap to build and operate. They offer an effective alternative technology for drying FS.

Several solar dryers have been reviewed by Perumal (2007) and Ekechukwu and Norton (1999) for commercial use, who concluded that forced convection dryers provide better control of the drying air, but require more energy. Diamante and Munro (1993) concluded that solar drying produces better quality product than open air sun drying. Prakash, Jha et al. (2004) and Kumar, Hebbar et al. (2006) have expressed concern that the high drying temperatures in solar dryers may cause damage to the quality of the dried product, therefore require constant monitoring.

Drying of FS using solar thermal energy offers an alternative method to the energy intensive treatment processes of FS, such as LaDePa. Drying of FS before reuse is a critical treatment step and is traditionally performed through the use of open air-sun drying technologies, such as drying beds in most developing countries. Use of drying beds faces the drawbacks of land requirements and lengthy drying times (Seck, Gold et al. 2015).

Although literature is available on the properties of FS, there is poor literature on the conventional and infrared drying of FS, no information is available on the drying kinetics of FS with respect to solar energy. This study is focused on characterising the solar drying characteristics of FS from VIP latrines in the eThekwini municipality through the analysis of the drying of FS in a custom designed solar dryer. This research work in the use of solar energy in FS treatment will assist in the efficient design and optimisation of solar energy based treatment methods. Figure 1-1 is a flow chart which describes the possible uses of excreta and highlights the criticality of drying in processes related to resource recovery.
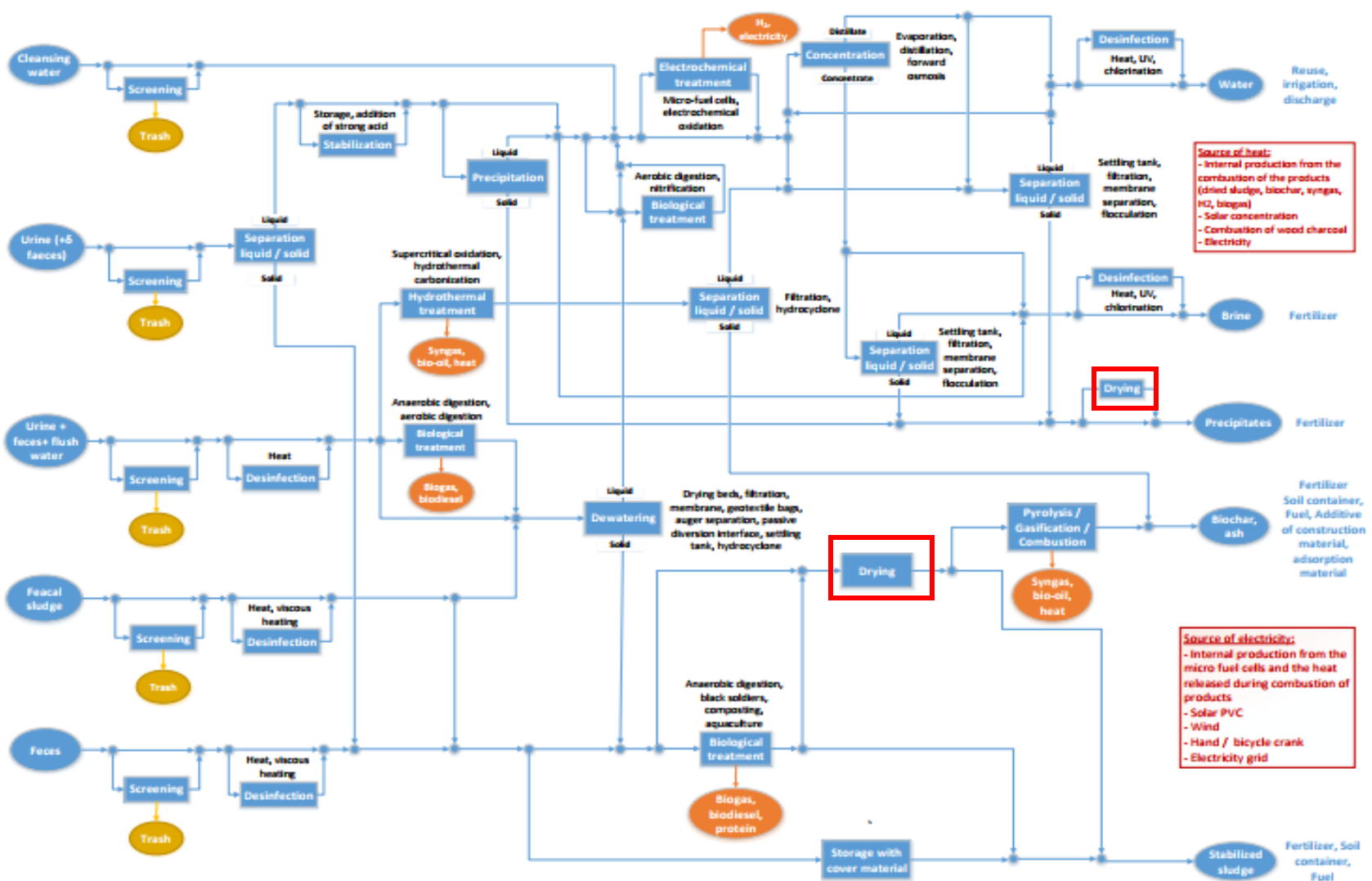
Figure 1-1: Flow Chart indicating the possible uses of excreta and highlighting the criticality of drying (PRG 2017)
Source: (Pollution Research Group 2017)

1.2   Aim of the study

The aim of this study is to characterise FS drying using solar thermal energy as solar drying is a promising alternative for FS treatment but there is lack of scientific data regarding the use of solar thermal energy. The data and knowledge generated will be useful for sanitation practitioners interested in the solar processing of faecal sludge for the improvement of the existing technologies designs or the development of technological innovations.

1.3   Scope of the study

The research will utilise FS sampled randomly from the pit emptying process of the eThekwini municipality of VIP latrines. Parameters applied in the investigation include the effects of varying weather conditions, airflow velocity, air preheating temperature, cross-sectional surface area, and sample thickness. The parameters were investigated for solar drying as well as open air sun drying.

The dependence on prevailing weather conditions, affected the repeatability of the experiments. Thermal properties, nutrient concentration and physical properties of the dried samples were analysed

1.4   Objectives

1.4.1   General objectives

- To evaluate the drying characteristics of FS sampled from ventilated improved pit (VIP) latrines in a custom designed solar drying system and to evaluate the effect of drying conditions on the properties of FS.

1.4.2   Specific objectives

- To design and build a solar dryer.
- To evaluate the effect of weather conditions, air flowrates, air temperature, geometry of sample and size of sample on drying rates as these are critical to drying times.
- To evaluate physico-chemical properties of the dried products, namely ash and moisture content, nutrient effects, density, shrinkage, calorific and thermal conductivity values as these are critical for the reuse of FS.

- To evaluate the qualitatively the effects of drying on the product, namely formation of a odours, crust and cracks as these are critical to both drying times and reuse requirements.

1.5   Outline of dissertation

Chapter 1 - Introduction

Introduces the study, providing the aim, scope and the objectives of the study.

Chapter 2 - Literature review

Provides a literature review on sanitation systems, paying particular focus to ventilated improved pit (VIP) latrines and its content, together with the associated management and resource recovery of FS. It also looks into drying technologies, with a particular focus on solar drying technologies as well as the drying concepts.

Chapter 3 - Materials and Methods

Explains the experimental apparatus and methods employed in the study to fulfil the objectives (of the study. The parameters used for the data analysis are also described. The chapter provides an insight into the design and commissioning of the rig and simulations for the design.

Chapter 4 - Results and discussion

Presents the major results and the subsequent discussion. The main trends deducted from the results are highlighted.

Chapter 5 - Conclusion and recommendations

The results are summarised and various conclusions drawn from the study are presented. The limitations of the current study and recommendations are provided.

CHAPTER 2: LITERATURE REVIEW

This chapter details the review of the relevant literature in order to understand the theoretical knowledge and state-of-art to achieve the desired goals. Individual aspects pertaining to the research study, namely, sanitation systems, ventilated improved pit (VIP) latrines and management of FS from VIP latrines, are presented and discussed. Solar energy and conventional drying technologies are addressed, followed by a review of solar drying technologies, drying concepts and the property and material related factors affecting solar drying of FS.

2.1 Faecal sludge (FS)

"*Faecal sludge is the crude or partially processed, semisolid or slurry, coming about because of the gathering, stockpiling and treatment of black water and excreta from sanitation units, with or without greywater*" (Strande and Brdjanovic 2014). FS contains all the contents of pits and vaults which gather faecal material in on-site sanitation establishments.

2.1.1 Sanitation systems

Sanitation systems are responsible for the capture, storage, treatment and disposal or reuse of human waste and wastewater. There are a variety of sanitation technologies available today. The variations result in a difference in convenience for the user, protection against the propagation of diseases, and water requirements during operation and use. As a consequence, sanitation technologies can be categorised in various ways. The main categories are:

- Waste disposal
- Water use
- Individual or communal use

2.1.1.1   Waste disposal

Sanitation systems can be categorised based on the manner of the disposal of waste material, which can either be related to the on-site technology or to the transport of the material to a different location. Thus, sanitation technologies can be divided into two categories:

- On-site sanitation systems
- Off-site sanitation systems

On-site sanitation systems dispose the waste on or close to the location of the sanitation system. On-site sanitation systems arise from the inability to transport or dispose of the waste away from the system. They are advantageous in providing improved sanitation systems at low costs. The major setbacks are the contamination of the environment, bad odours and insect breeding sites with the potential for collapse of the toilet structure. Septic tanks, latrines, including simple or traditional latrines and ventilated improved pit (VIP) latrines, are examples of on-site sanitation systems.

Off-site sanitation systems are sanitation technologies in which the waste is collected from the individual sanitation systems and carried away from the site to be treated and disposed of. These are normally connected to sewer networks and wastewater treatment plants (WWTPs). Sewer systems and bucket latrines are examples of off-site sanitation systems.

2.1.1.2   Water use

Sanitation systems can be categorised based on water usage. These can either be wet systems or dry systems. Dry sanitation systems do not utilise water as a carrier and the waste is broken down by anaerobic methods, through decomposition and/or dehydration. Wet sanitation systems utilise water to treat and transport the waste. VIP latrines fall under dry sanitation systems as no water is added to the system.

2.1.1.3 Individual or communal use

Sanitation systems can also be categorised through their application as either individual household or community sanitation systems. Sanitation systems classified under household sanitation systems include pit latrines, pour flush toilets as well as septic tanks which are built for use by an individual household. Systems such as communal toilets, bucket latrines and sewerage systems are classified as community sanitation facilities. VIP latrines can either be individual household or communal depending on application.

2.1.2 Ventilated improved pit (VIP) latrines

VIP systems are dry sanitation technologies, hence not requiring water input, and have been accepted as the standard for basic sanitation in South Africa (Buckley, Foxon et al. 2008).

2.1.2.1 Description of ventilated improved pit latrines (VIP latrines) and contents

VIP latrines are an improvement on standard/basic pit latrines. They are designed to reduce foul odours and the quantity of insects, e.g. flies, within the enclosure of the toilet. There are certain requirements for basic pit latrines to be qualified as a VIP latrine (Buckley, Foxon et al. 2008). A VIP latrine must:

   i.   Provide separation of waste from the users in a hygienic manner
   ii.   Include a ventilation pipe with a fly screen at the top-end
   iii. Must be constructed on a secure slab
   iv.   Must be private and dignified for the user

A standard VIP latrine comprises the pit, cover slab, superstructure, vent pipe with fly screen, pedestal, lid, roof and superstructure door (Buckley, Foxon et al. 2008). Figure 2-1 shows the basic structure of a VIP latrine.
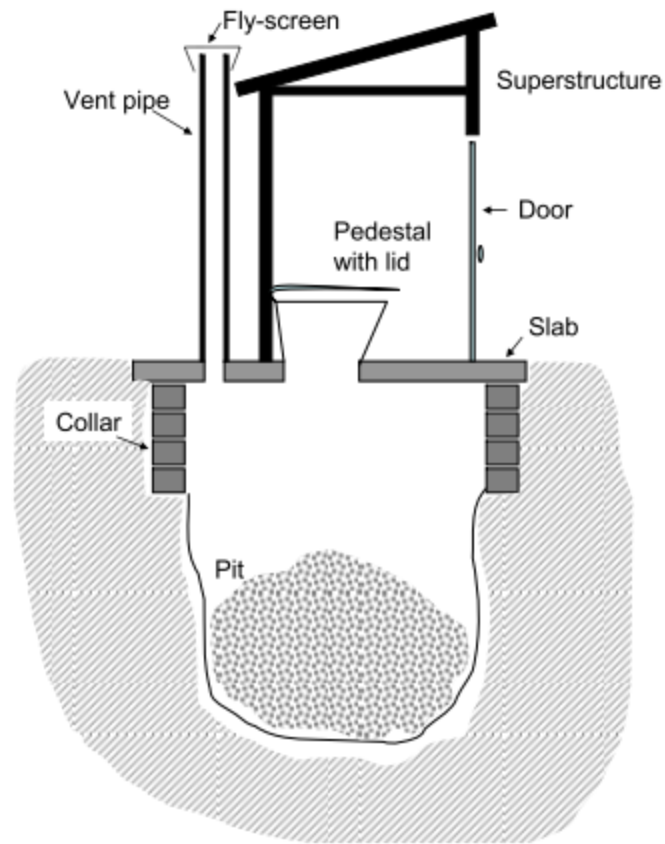
Figure 2-1: Ventilated improved pit (VIP) latrine basic structure
Source: Buckley, Foxon et al. (2008)

The components of the VIP latrine are explained as follows:

- Pit – the main purpose of the pit is the collection of the waste, it can be a single or twin pit with an open-top brickwork or blockwork. It should also be lined to avoid collapse.

- Cover slab – made from reinforced concrete with two openings for the pedestal and vent pipe.

- Superstructure – to provide privacy and weather protection. Can be made from the same build work as the house attached to the latrine.

- Vent pipe inclusive of fly screen – to control odours as well as insects such as flies. The pipe extends at least 500 mm above the roof of the toilet.

- Pedestal, lid, roof and superstructure door – to provide decency and privacy to the user.

There are several processes occurring in a VIP latrine. These include: gradual fill-up with faecal matter, water and other waste material, water transfer both into and out of the pit, as well as biological and physico-chemical transformations. Substantial volume reduction occurs though natural processes, such as anaerobic digestion, which slows down the fill-up rate but does not stop waste build-up (Buckley, Foxon et al. 2008). Table 2-1 shows the average fill up rates of pit latrines in different conditions of use.

Table 2-1: Fill up rates of pit latrines based on conditions present in the pit

CONDITIONS PRESENT IN PIT	RATE OF SLUDGE ACCUMULATION (l/year.person)
Waste retained in water where degradable anal cleansing materials are utilised	40
Waste retained in water where non-degradable anal cleansing materials are utilised	60
Waste retained in dry conditions where degradable anal cleansing materials are utilised	60
Waste retained in dry conditions where non-degradable anal cleansing materials are utilised	90

Source: Franceys, Pickford et al. (1992)

Pit contents are mainly composed of faeces, urine and biodegradable waste matter. Users also tend to use the pit as a waste/refuse disposal option resulting in the collection of non-biodegradable matter in the pit. The content varies within an individual pit and between various pit latrines. These variances include variation in appearance, chemical and physical characteristics. These differences are predominantly due to differences in user practises and geographical properties.

2.1.2.2 Physical and chemical characteristics of faecal sludge (FS) from VIP latrines

There are various ways to analyse and characterise FS. Buckley, Foxon et al. (2008) analysed FS from VIP latrines according to chemical oxygen demand (COD), biodegradability, characterisation of the solids, anaerobic and methanogenic activity.

Table 2-2 shows the average values of the characterisation of VIP FS from the study. The analysis was conducted on clean FS, which refers to FS that has been screened and sieved to remove all non-biodegradable matter.

Table 2-2: Characteristics of clean FS from pit latrines

ANALYSIS	AVERAGE VALUE	UNIT
Total COD	105	mg/g wet weight
Total COD	445	mg/g dry weight
Soluble COD	31	% of total COD
Moisture content	76	% of wet sample
Total solids	33	% of wet sample
Organic solids	36	% of solids
Inorganic solids	64	% of solids
Soluble nitrates	0.028	mgN/g wet sample

Source: Buckley, Foxon et al. (2008)

FS, similar to animal excreta, is rich in nutrients. These nutrients can be utilised to supplement or substitute synthetic fertilisers. The nutrients can be water soluble or insoluble. Zuma, Velkushanova et al. (2015) analysed the chemical and thermal properties of FS from ventilated improved pit latrines within the eThekwini municipality. Properties analysed included moisture content, ammonia, total Kjeldahl nitrogen (TKN), orthophosphates, thermal conductivity and calorific values. Moisture content varied in terms of position in the pit, with 60 % to 70 % recorded at the bottom and 80 % to 90 % recorded at the top (Bakare, Foxon et al. 2012; Zuma, Velkushanova et al. 2015). The moisture content differs with height but is constant with horizontal position. TKN varied between 4 mg/g to 14 mg/g of wet sludge, ammonia recorded a maximum value of 5.87 mg/g of wet sludge to a minimum of 0.1 mg/g of wet sludge. Orthophosphates were found to be lower than 0.06 mg/g of wet sludge. Thermal conductivity values ranged between 0.51 W/m.K and 0.59 W/m.K and calorific values between 0.0029 MJ/g and 0.0238 MJ/g of dry sludge (Zuma, Velkushanova et al. 2015).

In summary, although moisture content showed variation as a function of the height in the pit, such variances were not noticed for the nutrient concentrations, thermal conductivity and calorific values.

Table 2-3 shows a summary of other research work on wet human excreta (wet refers to the samples not being exposed to drying before analysis).

Table 2-3: Characteristics of wet human excreta

PARAMETER	SOURCE			
	(Nwaneri 2009)	(Gantzer, Henny et al. 2002)	(Lopez Zavala, Funamizu et al. 2002)	(Almeida, Butler et al. 1999)
Moisture content	78%	-	81.8%	79.2%
Total solids	22%	-	18.2%	20.8%
Volatile solids	-	-	84.4%	-
Total COD	1.11mg/mg	0.57mg/mg	1.45mg/mg	1.38mg/mg
Dissolved COD	0.37mg/mg	0.09mg/mg	-	-
Suspended COD	0.67mg/mg	0.46mg/mg	-	-
Volatile fatty acids	-	8.46 gCOD/l	-	1.5gCOD/l
Total nitrogen	-	17.82mg/g	60.1mg/g	-
Ammonia-nitrogen	-	-	3.4mg/g	7.2mg/g
Nitrate-nitrogen	-	-	0.03mg/g	0.14mg/g
pH	-	-	7.5	-
Sulphate ions	-	-	1.1mg/g	-
Chloride ions	-	-	4.2mg/g	-

Nutrient capacity of FS after treatment is critical for resource recovery as a fertiliser or soil conditioner. Mnkeni and Austin (2009), Nikiema, Cofie et al. (2013), and Komakech, Banadda et al. (2014) analysed the nutrient concentration in dried FS samples. Parameters analysed included phosphorus, potassium, calcium, magnesium, orthophosphates and nitrates. Mirara (2017) and Makununika (2016) analysed similar nutrients using samples from VIP latrines in the eThekwini municipality. Table 2-4 shows a summary of the results from their findings.

Table 2-4: Characteristics of dried FS samples

NUTRIENT	SOURCE				
	(Makununika 2016)	(Mirara 2017)	(Komakech, Banadda et al. 2014)	(Nikiema, Cofie et al. 2013)	(Mnkeni and Austin 2009)
	(mg/kg dry solid)	(mg/kg dry solid)	(mg/kg dry solid)	(mg/kg dry solid)	(mg/kg dry solid)
P	7.2	6.0	2.7	12.4	3
K	8.6	8.0	19.5	6.1	4.4
Ca	42.1	35	-	-	4
Mg	11.2	12.5	-	-	7.9
PO_4^{3-}	2.3	5.0	0.37	-	-
NO_3^-	0.5	0.3	-	2.9	-
NH_3	4.5	5.0	-	-	-

Thermal characterisation of FS is critical for the design and building of treatment facilities. Table 2-5 shows a summary of the results of the studies of Zuma, Velkushanova et al. (2015), Makununika (2016) and Mirara (2017). The volatile solids were found to greatly affect calorific values (Makununika 2016). Thermal conductivity showed a high dependence on the moisture content of the sludge (Makununika 2016; Mirara 2017; Zuma, Velkushanova et al. 2015).

Table 2-5: Thermal characterisation of wet and dry VIP FS

PROPERTY	SOURCE		
	(Makununika 2016)	(Mirara 2017)	(Zuma, Velkushanova et al. 2015)
Calorific value	12.5MJ/kg (w.b)	15-25MJ/kg(d.b)	4.9-19.3MJ/kg (d.b)
Thermal conductivity	0.044W/m.K (w.b)	0.06W/m.K (w.b)	0.42-0.59W/m.K (w.b)
Heat capacity	220J/kg.K (w.b)	400J/kg.K (w.b)	1.87-4.73kJ/kg.K(w.b)
Ash content	-	30% (d.b)	-
Volatile solids	0.47g/g (d.b)	70% (d.b)	0.45-4.3gVS/g ash

d.b-dry basis, w.b-wet basis, VS-volatile solids

2.1.2.3 Management, treatment and resource recovery from ventilated improved pit (VIP) latrine faecal sludge (FS)
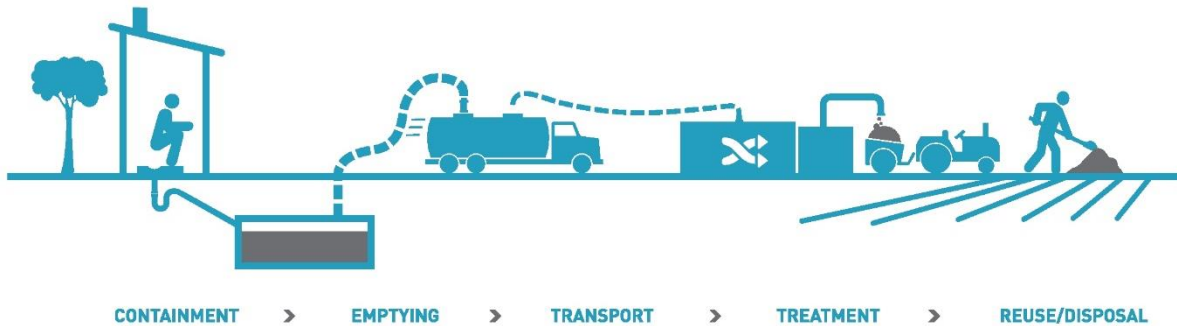
Figure 2-2: FSM flow chart

FS starts as an unavoidable waste resulting from the use of pit latrines. The present management systems of FS has been fragmented and improper with attendant poor health and environmental problems. Figure 2-2 shows a FSM flow chart.

Due to the nature of FS, it can be utilised for various applications. The difficulty in promoting these applications is mainly due to the view of FS as waste and not a resource for harnessing. The design of FS management systems for resource recovery can lead to the development of viable business models (Diener, Semiyaga et al. 2014). FS can be utilised as a combustion fuel, for production of biogas as a result of anaerobic digestion, for derivation of protein for use as animal feed or as an organic fertiliser and for soil conditioning (Muspratt, Nakato et al. 2014; Werther and Ogada 1999; Čičková, Newton et al. 2015;, Vinnerås, Palmquist et al. 2006; Moe and Rheingans 2006; Mihelcic, Fry et al. 2011; Malkki 1999; Niwagaba 2007).

Traditional disposal methods of VIP FS include the covering up of the full pit and construction of a new one, or emptying of the pit and disposal of the FS in an off-site facility. Still, Foxon et al. (2012) lists alternatives such as burial in an on-site pit, anaerobic digestion to produce biogas, treatment in a wastewater treatment plant (WWTP), use of the black solder fly, deep row entrenchment and composting. Williams (2013) suggested the recovery of energy through thermochemical processes such as pyrolysis, combustion and gasification. Sevilla and Fuertes (2009) suggested the use of anaerobic digestion to produce methane and recoup biogas, but this requires the addition of water which is counterproductive as it is easier to handle, transport and dispose of dry materials.

FS has different properties to sewage sludge; FS is 10 to 100 times more concentrated than sewage sludge; 1.5 m^3 of FS is approximately equivalent to 1000 m^3 of sewage sludge, which is mainly due to the lack of water content in FS. FS has non-biodegradable material in it due to the use of the pit as a disposal option. As a result, disposal into wastewater treatment plants causes shock loading to the wastewater treatment plant system (Still, Foxon et al. 2012).

Wastewater treatment plant sludge (biosolids) has been applied as an alternative fuel source in Europe and the US for the cement industry (Boesch and Hellweg 2010). Technical viability for the application of FS as a fuel has been demonstrated through laboratory and pilot scale research in Dakar, Senegal, and Kampala, Uganda (Gold, Niang et al. 2014). The average calorific value of FS is 17 MJ/kg (Muspratt, Nakato et al. 2014) compared to 8 MJ/kg to 23 MJ/kg for biosolids (Modinger and Mayr 2006; Spinosa and Vesilind 2001). For combustion resource recovery, sludge should be dried to a minimum of 28 % moisture content (Muspratt, Nakato et al. 2014).

Deep row entrenchment is the burying of FS in 20 m long, 0.6 m wide and between 1.2 m to 1 m deep trenches. This results in an improved soil fertility as FS acts as a slow release fertiliser. This has massive benefits for the agroforestry sector as it increases the growth rates of the trees and helps in the recovery of wasteland such as mine spills (Still, Foxon et al. 2012). A drawback is that FS is biological waste that then requires the addition of disinfectants and antibacterials as it might contain harmful pathogens.

FS waste can also be incinerated to reduce the volume, form charcoal and tar, and the resultant ash will be buried in landfill sites. This is achieved through pyrolysis and gasification. Pyrolysis is the degradation of organic waste thermally without oxygen to produce carbonaceous charcoal, tar and combustible gases. Gasification is the thermal degradation of organic waste in the context of a limited supply of oxygen and in the presence of steam or carbon dioxide to produce tar, ash and a gaseous fuel composed mainly of hydrogen and carbon monoxide (Williams 2013).

Creation of biogas from FS is through anaerobic digestion. Small scale digesters utilising human excreta and animal waste as feed are in use in Ghana (Box 2010). Anaerobic digesters are mainly applied for wastewater treatment with research currently being conducted to access the feasibility for adoption of anaerobic digesters for FS treatment.

Hydrothermal carbonisation is the process in which organic material is decomposed in water at temperatures between 150 °C and 350 °C to form a high carbon content product (Sevilla and Fuertes 2009). Supercritical water oxidation utilises water at temperatures and pressures above 374 °C and 221 bar to decompose organic compounds which enables energy recovery while an organic stable material is produced (Gidner, Stenmark et al. 2001; Veriansyah and Jae-Duck 2007).

FS can be applied as feed stock to insect larvae for protein generation as animal feed. Agriprotein applies the black soldier fly larvae (BSFL) to treat and process FS for the production of chicken and/or fish feed (Van Huis, Van Itterbeeck et al. 2013). This follows on from insect larvae being widely cultivated for animal feed in aquaculture, frog and chicken farms utilising municipal waste as feed (Calvert, Martin et al. 1969; Hem, Toure et al. 2008; Ogunji, Nimptsch et al. 2007; St-Hilaire, Sheppard et al. 2007). Application of BSFL is an example of conversion of organic refuse by saprophages (CORS) technology. The larvae feed on organic material and can be applied to the treatment of FS. Resource recovery occurs during the harvesting of the prepupae as they migrate from the feedstock to pupate. The prepupae contain 44% crude oil and 33% fat, so can be applied as animal feed and for biodiesel production (St-Hilaire, Sheppard et al. 2007).

Thermal drying can be utilised on faecal sludge, a example is the latrine dehydration and pasteurization machine (LaDePa). LaDePa is used to process FS into pasteurised dry pellets. The resulting pellets can be utilised in agricultural crop production or as a fuel (Harrison and Wilson 2012). Figure 2-3 shows the schematic of the LaDePa. The machine applies infrared radiation to dry and pasteurise FS pellets using medium infrared radiation lamps. Tests performed on the LaDePa machine have demonstrated the efficient deactivation of Ascaris eggs present in FS.
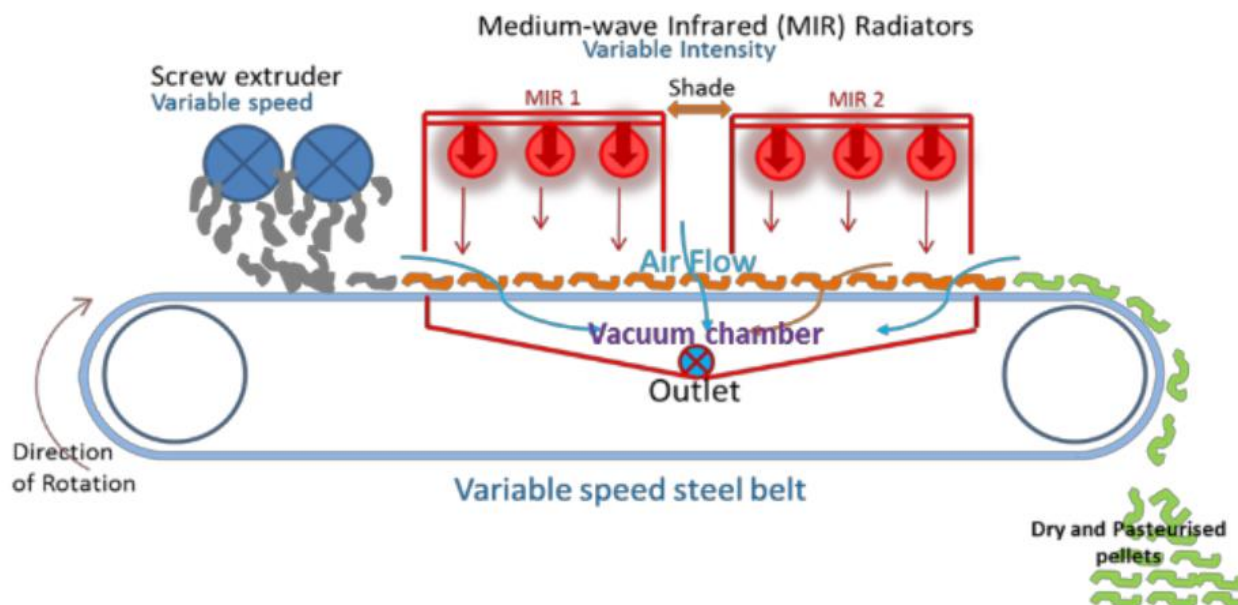
Figure 2-3: Schematic of the LaDePa machine
Source: Harrison and Wilson (2012)

The application of drying beds in FS management is as a treatment method aimed mainly at dewatering the FS. The age of FS and the period of on-site storage have an effect on the ability to dewater as it affects the stability of the sludge (Singh, Mohan et al. 2017). Drying beds can either be unplanted or planted drying beds. Unplanted drying beds utilise shallow beds which are filled with sand and gravel, and fitted with an underdrain to collect the resulting leachate. The leachate requires further treatment before disposal and/or resource recovery as it still contains pathogens (Cofie, Agbottah et al. 2006).

A planted drying bed, also known as a vertical-flow constructed wetland, applies the use of emergent plants such as *Andropogon gayanus* to treat the FS (Joceline, Koné et al. 2016). The emergent plants are critical to the operation of planted drying beds in regards to waste stabilisation and pathogen reduction (Strauss, Larmie et al. 1997). Advantages of drying beds include low cost, good dewatering efficiency, no energy requirements, cost effectiveness, ease of operation and ability to handle high loading rates. The disadvantages include high labour intensity, limited pathogen reduction, high land requirements and the need for post treatment. Figure 2-44 shows the scheme of a basic vertically constructed wetland.
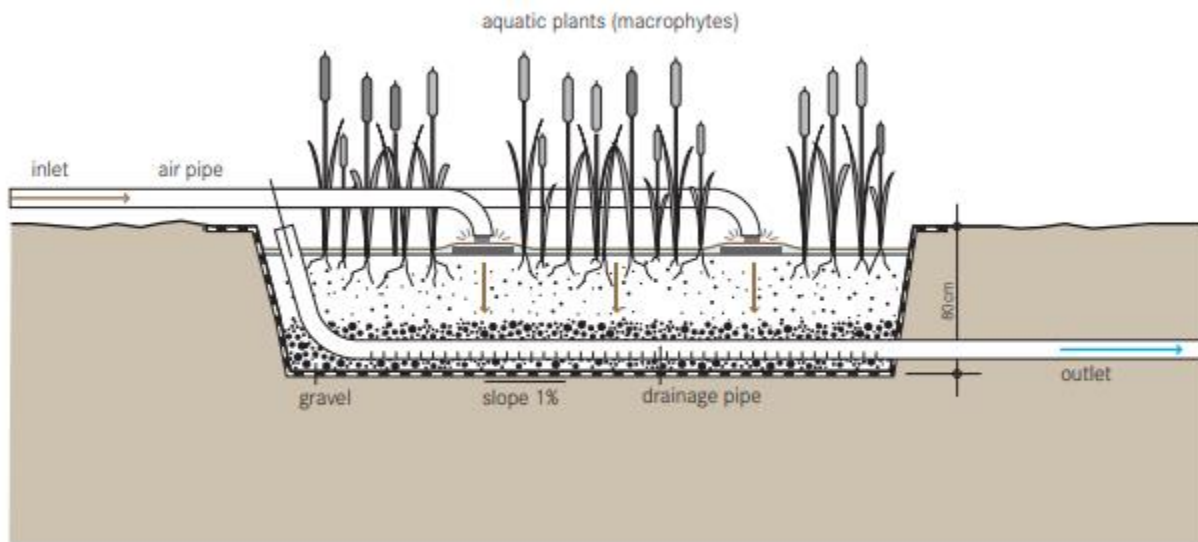
Figure 2-4: Vertical flow constructed wetland
Source: Tilley (2008)

Table 2-6 show a selection matrix for FS treatment methods based on existing constraints at the treatment site, highlighting dependence on CAPEX, OPEX, skill, land and energy requirements and indicating capacity for resource recovery.

Table 2-6: Selection matrix for FS treatment methods based on existing constraints

TREATMENT METHOD	CONSTRAINTS					
	Land requirement	Energy requirement	Capital expenditure	Operation expenditure	Skill requirement	Resource recovery
Unplanted drying bed	H	L	L	L	L	M
Planted drying bed	H	L	L	L	L	M
Centrifugation	L	H	H	H	M	L
Settling-thickening tank	L	L	L	L	L	M
Imhoff tank	L	L	M	M	H	M
Geobag	H	L	M	M	L	L
Co-composting	H	L	H	H	L	H
Deep row entrenchment	H	L	L	L	L	L
Vermicomposting	H	L	H	H	M	H
Anaerobic digester	L	L	H	H	H	M
Shallow trenches	H	L	L	L	L	L
Solar sludge oven	L	L	M	L	M	H
Black solder fly larvae (BSFL)	H	L	H	H	M	H
Solar drying	H	L	M	M	M	H

H-high, M-medium, L-low
Source: Harrison and Wilson (2012)

2.2 Solar energy

Globally, many countries have begun to address the challenge of sustainable energy application through adjustments of energy consumption methods with the goal to uphold social, ecological and financial components of sustainable development. Energy solutions based on fossil fuels such as oil, coal and natural gas have resulted in an increase of the amount of greenhouse gases released into the atmosphere. Fossil fuel deposits are also in course of depletion, which will result in exorbitant operation costs for energy dependent processes which depend on fossil fuel energy. The earth receives more energy from solar irradiance in 1 hour than the yearly energy requirements (Thirugnanasambandam, Iniyan et al. 2010).

There is growing interest in alternative sources of energy, such as solar and wind energy, in both the developed and developing countries (Power 2010). Solar energy is a highly promising renewable energy resource for the generation of power. Solar energy represents the largest energy inflow into ecosystems. After reflection and absorption in the atmosphere, a significant amount of solar energy is received on the earth's surface and utilised for the development of living organisms (Bosshard, Hermann et al. 2006). As a green energy source, solar energy is environmentally friendly, as it possesses a low carbon footprint as well as low pollutant emissions.

Despite the availability and capacity of solar resource with potential to supply energy on a global scale, generation of solar energy based power is still low compared to other energy resources. The main constraints have been due to the relatively high capital cost required to implement solar systems, although solar energy technologies used to harness solar energy are now becoming more cost effective. The intermittent nature of solar energy availability results in the requirement of energy storage systems and subsequently relatively low power density (Bosshard, Hermann et al. 2006).South Africa experiences, in average, over 2 500 hours of sunshine per solar year and solar irradiation at the surface ranges from 4.5 to 6.5 kWh/m^2/day (Fluri 2009; Zawilska and Brooks 2011).

2.2.1   Types of solar energy systems

Solar energy systems can be classified according to two categories:

- Thermal systems which convert solar energy into thermal energy
- Photovoltaic (PV) systems which convert solar energy into electrical energy

2.2.1.1   Solar thermal systems

Solar thermal systems utilise solar radiation for thermal energy generation. The incident solar radiation can be collected and focused and collected by a variety of techniques (Alsharkawi and Rossiter 2016). Thermal power systems based on solar energy can be designed to satisfy demand during daylight hours and can be coupled with energy storage systems to ensure that their operation can be extended to 24 hours of operation while meeting the base load requirements (Chaanaoui, Vaudreuil et al. 2016). The excess heat collected during the system exposure to solar radiation can be stored in liquid, solid or phase changing media like molten salts, ceramics, concrete, and can then be utilised during periods where the solar radiation received is not sufficient to operate the required processes (Timilsina, Kurdgelashvili et al. 2012). There are different applications for thermal energy systems, for example generation of power, water heating in households, and cooking applications.

Solar thermal energy can be harnessed by solar thermal collectors or solar thermal concentration onto a focal point. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers it to a fluid (usually air, water, or oil) flowing through the collector. Solar thermal concentration is the use of reflectors to focus solar irradiation to concentrate the energy received at the focal point. These systems can be merged so that the solar energy is focused onto the collector (Alsharkawi and Rossiter 2016).

2.2.1.2 Photovoltaic (PV) systems

Photovoltaic (PV) energy capture is the conversion of solar irradiance directly into electricity. PV systems directly convert solar radiation using specially designed cells (Maycock 2005). The intensity of the incident radiation determines the electricity produced. PV system cells are made of layers of semi-conductor material (Sahoo 2016). The costs of PV systems are currently declining due to the improvement in PV technology with continuous research and increase of efficiency (Tyagi, Rahim et al. 2013).

2.2.2 Drying

Drying is the removal of moisture from a substance to a desired level within a certain period of time (Ekechukwu and Norton 1999).

Drying is applied in various processes in the chemical, agricultural, pharmaceutical, mineral and wood processing industries (Mujumdar 2006). When a material is exposed to air at a particular temperature and humidity, the material will either gain or lose moisture until an equilibrium condition is achieved between the drying substance and the surrounding air (Coulson 1999). Two processes take place simultaneously during drying: heat transfer from the heat source to the sample (this can be through conduction, convection or/and radiation), and a mass transfer from the wet material to the surrounding air (Perumal 2007). During drying, the substance to dry tends to form a dry surface layer, a crust, which is resistant to moisture transfer if the drying rate is too high. As a result, to avoid this effect, the drying rate must be controlled to guarantee optimum rates (Arinze, Schoenau et al. 1979).

Drying is a highly energy intensive process. Several research works have been conducted to analyse possible energy alternatives and optimisation of current processes. The optimisation of dryers requires in-depth and complete knowledge and understanding of the drying process. Energy savings, improved product quality and avoidance of environmental pollution are possible through utilisation of renewable energy technologies (Icerman and Morgan 1984, Basunia and Abe 2001).

Use of renewable energy technologies to replace conventional energy systems has received increased attention recently due to their potential to meet the basic needs of many countries (Banerjee 2005).

2.2.2.1 Drying technologies

Methods of drying include open air sun drying, solar drying, radiative drying, hot air convective drying, oven drying and freeze drying.

2.2.2.1.1 Open air sun drying

Open air sun drying is the most common drying method applied in tropical and sub-tropical countries. It involves the laying out of produce in thin layers exposed to direct sun and wind (Mustayen, Mekhilef et al. 2014). Open air sun drying depends on the environmental conditions of solar irradiation, wind and other ambient conditions (Panwar, Kaushik et al. 2012). The advantages of open air sun drying include simplicity and low costs. The disadvantages of open air sun drying include the need for a large surface area, decreased product quality due to lack of environmental protection, uneven drying and it is highly labour intensive.

2.2.2.1.2 Radiative drying

The wavelength of waves utilised distinguishes microwave from infrared drying. Microwave drying utilises a wavelength between 0.025 microns to 0.75 microns, falling between radio and infrared waves. Thiagarajan (2008) reported a 75 % energy saving when applying microwave drying compared to traditional thermal drying techniques. Microwave electromagnetic radiation has the ability to penetrate within the solid exciting dielectric molecules and causing a temperature rise. This provides the required energy for the heat and mass transfer processes during drying. Application of microwave radiation is common in food processing as it retains the texture and taste of food (Thiagarajan 2008).

Infrared radiation applies surface heating as infrared waves cannot penetrate into the surface. The depth of infrared penetration is limited, depending on the properties of the substance and type of infrared radiation.

2.2.2.1.3 Hot air convective drying

Hot air convective drying utilises heated air as the energy source to drive the heat and mass transfer processes. The heated air flows through the material or over the surface to enable air-to-surface contact for the heat transfer to the material and mass transfer to the drying air. The drying rate is dependent on the physical properties of the air and the material. Due to the high energy costs of air preheating, exhaust gases are commonly applied. Hot air convective drying is used mainly for the drying of wastewater sludge(Makununika 2016).

2.2.2.1.4 Freeze drying

For processes requiring drying but with possible negative effects if heat is applied, freeze drying (lyophilisation) can be employed. Freeze drying involves exposing a substance to conditions below the triple point of the moisture (Dail, He et al. 2007), to lead subsequently the direct conversion of moisture from its solid phase to gaseous phase. This process is commonly applied in the manufacture of pharmaceuticals, biological substances and specialised food products (Sistani, Rowe et al. 2001).

2.3 Solar drying

Solar drying is the application of solar energy to the drying processes. The main parameters influencing the rate of solar drying are the solar irradiance, air temperature, ventilation rates and the moisture content of the sample. Solar energy is utilised as either the sole source of the required heat energy or as a supplemental energy source. Airflow circulation is either conveyed by natural or forced convection. The process can also utilise the application of preheated air through the product, direct exposure to solar irradiation or a combination of both (Ekechukwu and Norton 1999). Ultimately, the major requirement is the transfer of heat to the sample which can either be by convection, conduction and/or radiation (McLean 1980). During direct radiation drying, part of the solar irradiance may be absorbed by the sample, thereby generating heat in the interior of the product as well as at the surface which enhances the heat transfer and increases the drying rate (Basunia and Abe 2001).

Solar drying is an alternative option to traditional drying techniques and is a contribution towards the solution of open air sun drying problems. The driving factors behind solar drying are:

- Solar drying provides the desired reduction of moisture together with improved quality of the dried products;
- Drying times are improved, enabling the processing of higher volumes of sample;
- Improved pasteurization capacity due to higher temperatures in the dryer;
- Reduction in cost of sample treatment;
- Additional costs involved in installing solar dryers can be recuperated by reduction in the processing costs.

2.3.1 Components of solar dryers

Solar dryers comprise the following main parts:

- Drying space, where the moist material to be dried is placed and where the drying phenomenon takes place;
- Collector to absorb and convert solar radiation into heat;
- Heat transfer equipment for transferring heat to the drying air or to the material;
- Means for keeping the drying air in flow, for example a fan;
- Ducts, pipes, and other appliances;

- Auxiliary energy source (optional);
- Heat storage unit (optional);
- Measuring and control equipment (optional).

2.3.2 Classification of solar dryers

A considerable amount of research work has been devoted to solar drying, mainly focused on the drying of agricultural products (Tomar, Tiwari et al. 2017; Perumal 2007). A variety of low-cost solar dryers have been developed, ranging from basic simple wooden cabinets with transparent covers to hybrids with thermal storage systems (Ekechukwu and Norton 1999; Kant, Shukla et al. 2016). The structure of solar dryers is adjusted to the quantity, characteristics, and particularities of the material to be dried as well as to the energy sources used. Solar dryers are grouped into three main categories based on their operation characteristics. These are:

- Solar natural dryers;
- Semi-artificial dryers;
- Solar-assisted artificial dryers.

Solar natural dryers are solar dryers using ambient energy sources only. These have 2 subdivisions:

- Passive natural convection solar dryers; cabinet, tent type, greenhouse type, chimney-type dryers. The limitations are the need for constant direct radiation on the material to dry and low airflow rates. Airflow is induced by natural convection due to the temperature gradient. These are cheap and simple to construct.
- Active, partly forced convection solar dryers; these have a fan driven by electrical energy converted by PV cells or by a small turbine.

Semi-artificial solar dryers are solar dryers which apply a small amount of external power in the system. These may apply a fan driven by an electric motor to maintain a continuous air flow through the system. Solar-assisted artificial dryers are dryers which apply solar energy as an auxiliary energy source.

The three main classifications of solar dryers are further divided into three subdivisions based on the method of drying. The subdivisions are:

- Direct dryers;
- Indirect dryers;
- Mixed dryers.

2.3.2.1 Direct dryers

Dryers in which the material to be dried is directly exposed to solar radiation are termed direct solar dryers. The dryers consist of a base frame with a transparent cover panel and/or side panels. To further enhance the efficiency of the dryer, the internal surfaces of the enclosure are dark covered to enhance absorption of the energy and reduce reflective losses. The heat generated from the absorption of the solar radiation within the material as well as the surfaces of the solar dryer causes the removal of moisture (Onyegegbu, Morhenne et al. 1994). Figure 2-5 shows a direct solar dryer.

Direct dryers are basic and simple to construct. They can heat the drying material to temperatures higher than those achieved by sun drying (Tiwari and Ghosal 2005). However, they are known to suffer from many problems some of which are slow drying and overheating. Unless they are built in large sizes, they can only dry small quantities of drying material, because they use the same ground area that traditional sun drying requires, but they exhibit higher drying rates per unit area than traditional drying systems (Ghaffari and Mehdipour 2015; Jayaraman, Das Gupta et al. 2000). Another major disadvantage of direct dryers is the difficulty in controlling the rate of moisture removal as it dependence on the solar irradiance (Fudholi, Sopian et al. 2010).

At the start of the drying process, it is often necessary to close all the outlet air holes to allow the temperature of air in the dryer to rise. Water evaporates from the crop and condenses on the inside of the transparent cover thus reducing the amount of solar radiation transmitted to the dryer interior. This condition is subsequently improved by opening the outlet vents, but in turn it causes the temperature inside the dryer to fall.
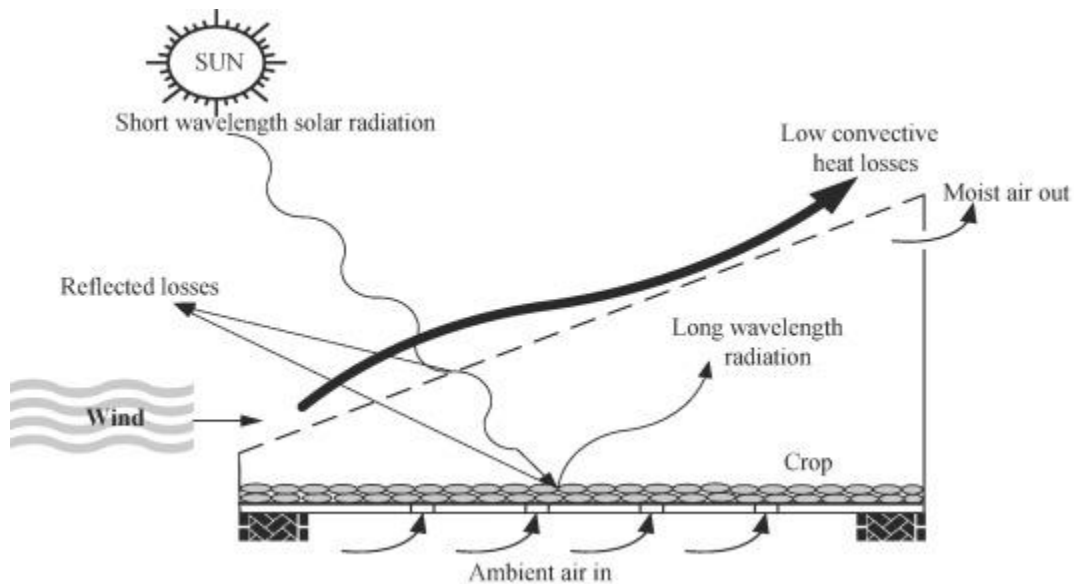
Figure 2-5: A direct solar dryer
Source: Tomar, Tiwari et al. (2017)

2.3.2.2 Indirect dryers

Indirect solar dryers are those in which the drying material is placed in an enclosed drying cabinet thereby being shielded from direct exposure to solar radiation. An indirect solar dryer consists of two major components: a solar powered air heater which is used to raise the temperature of the drying air, and a drying chamber which is the enclosure that accommodates the material for drying (Jain and Tewari 2015). A chimney is usually incorporated in natural convection indirect dryers to increase the airflow through the drying space. Air heated in the collector passes through the drying chamber where the material to be dried is placed on one or more porous trays. The air passes through the wet drying bed and becomes nearly saturated, thus lowering its temperature to nearly that of the ambient air, before it exits via a chimney (Pangavhane, Sawhney et al. 2002). Figure 2-6 shows an indirect solar dryer.

This type of dryer is used when the material being dried can be damaged if it is exposed to the sun direct rays. The drying material can be dried in layers, therefore saving ground space. However, natural convection indirect solar dryers are prone to poor performance. Since the air above the drying bed is not substantially different in temperature from that of the ambient air, which is also damp in humid regions, the resulting buoyancy forces, which are proportional to the temperature difference, are very small, and in turn produce very low airflow rates (Kant, Shukla et al. 2016; Condorí, Duran et al. 2017).
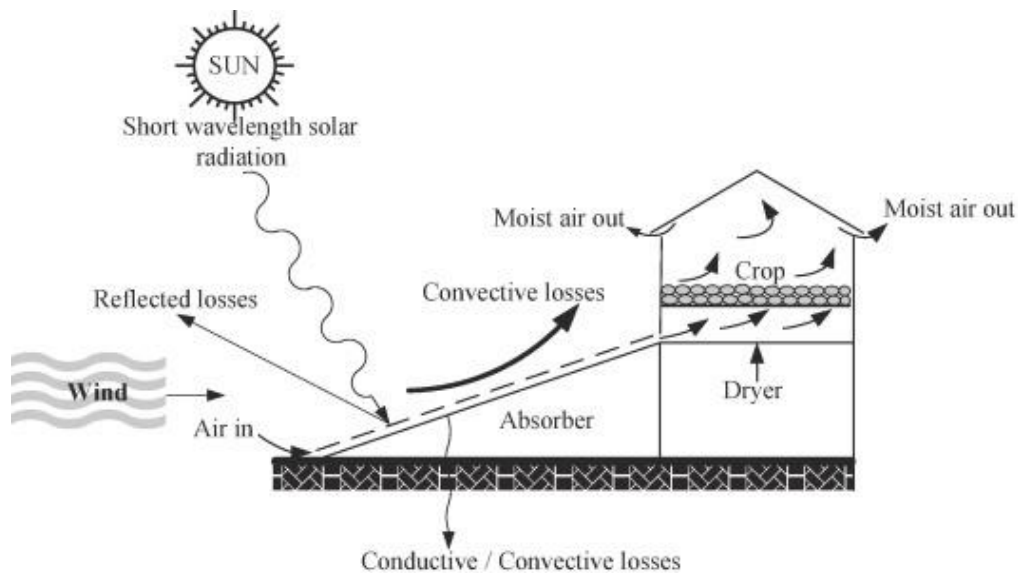
Figure 2-6: Indirect solar dryer
Source: Tomar, Tiwari et al. (2017)

2.3.2.3 Mixed dryers

A combination of direct and indirect solar dryers is termed mixed mode dryers. They normally are indirect dryers with transparent drying chamber tops and/or sides. Mixed mode dryers are best suited to drying material to which the exposure to sunlight is considered essential to achieve the required drying standards (Archuleta, Berkey et al. 1983; El-Sebaii, Aboul-Enein et al. 2002; Simate 2003). Figure 2-7 shows a mixed solar dryer in application for ginger slices.
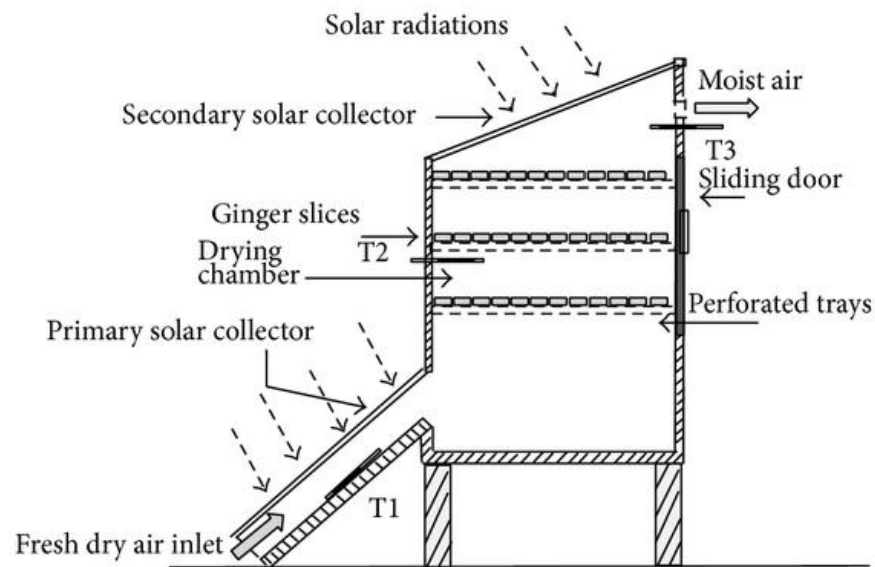
Figure 2-7: Mixed solar dryer
Source: Deshmukh, Varma et al. (2014)

2.3.3 Factors affecting solar drying

Drying is essential in various applications. There are several factors affecting the performance of solar drying. These include:

- Psychometry of the air present in the solar dryer;
- Drying properties of the material to be dried;
- Solar irradiance received at site.

2.3.3.1 Psychometry

The psychometry of the air refers to the thermodynamic properties of the air-vapour mixture under different operating conditions (Alahmer, Omar et al. 2011). The more dry the air in the solar dryer, the greater the drying rate. The specific humidity of the surrounding air increases due to moisture evaporation until thermal equilibrium (Tomar, Tiwari et al. 2017).

2.3.3.2 Drying properties

The presence of bound and unbound moisture in the product affects the drying rate as bound and unbound moisture exert different equilibrium vapour pressures (Sodha, Dang et al. 1985).

2.3.3.3 Solar irradiance

The solar irradiance affects the use of solar drying technologies, as different climates and locations receive different irradiance values.

Solar drying exhibits various advantages and disadvantages. Advantages of solar drying include (Mühlbauer, Esper et al. 1993):

- Improvement in the quality of dried products;
- Reduction of operating costs as solar energy is a clean and free source of energy;
- Protection of products from the environment enabling overnight/continuous drying
- Reduces dependence on fuel and as a result reduces environmental impact;
- Cost effective.

The disadvantages experienced by solar drying include:

- Lack of consistency on energy source;
- Requires adequate solar radiation;
- Long drying times.

2.3.4   Application of solar drying

Most of the work related to solar drying has been conducted in the agricultural field to preserve and store farm produce. Various investigations have shown that solar drying can be an effective method for drying farm produce and as an aid in food preservation as well as improving the product quality as it is protected against environmental impacts (Perumal 2007). The orientation of the solar dryer is critical for performance optimisation. For winter periods, above 40º to 45º latitude, an east-west alignment maximises solar radiation collection. In summer periods, a north-south orientation maximises solar radiation collection (Walker and Duncan 1974).

A direct natural convection solar dryer was able to dry 100 kg of tapioca in 20 hours (a two day drying period) using a surface area of 7.56 m^2 from an initial moisture content of 79 % to 10 % in wet basis. This translated to an average drying rate of 0.456 kg/h.m^2. The average operating ambient conditions for temperature and relative humidity were 32 °C and 74 % respectively. Daily global solar radiance incident on a horizontal surface was recorded at 13 MJ/m^2.day. The testing was conducted in Warri, Nigeria (Ogheneruona and Yusuf 2011).

Akoy, Ismail et al. (2006) applied a natural convection solar dryer to mango slices with a collector surface area of 16.8 m^2. The moisture content of the slices was reduced from 81.4 % to 10 % moisture content on a wet basis in a period of 2 days (20 hours). The average operating ambient conditions for temperature and pressure were recorded as 30 °C and 15 % respectively. Daily global solar radiance incident on a horizontal surface was recorded at 20 MJ/m^2.day. The testing was conducted in Khartoum, Sudan.

An indirect forced convection solar dryer integrated with a heat storage system dried red chillies from 72.8 % to 9.5 % wet basis moisture content. The moisture content was reduced in 24 hours of drying, achieving a moisture extraction rate of 0.87 kg/kWh. The system consisted of a flat plate solar air heater coupled with a heat storage unit, a drying chamber and an air blower. The heat storage system extended the available drying time by 4 hours. The testing was conducted in Pollachi, India (Mohanraj and Chandrasekar 2009).

A mixed mode solar dryer constructed by locally sourced materials was applied to dry yam and achieved an 85.4 % reduction in moisture content at a rate of 0.62 kgh-l. The dryer was constructed with transparent walls and roof. Heated air from the solar collector was passed through a grain bed housing the yam, at the same time, the yam also received direct solar radiation through the transparent covers. The temperature profiles inside the dryer, the collector and ambient conditions showed a higher temperature in the dryer and collector than ambient conditions (Bolaji and Olalusi 2008).

Forson, Nazha et al. (2007) applied a mixed mode dryer to cassava, resulting in a reduction in moisture content in wet basis from 67 % to 17 % in a drying time of 30 hours to 36 hours. 160 kg of cassava was dried, with 100 kg of moisture lost, utilising a surface area of 42.4 m^2. Operating ambient conditions of temperature and relative humidity were measure at 28.2 °C and 77.8 % respectively. The average solar irradiance was measured at 340.4 W/m^2. The testing was conducted in Kumasi, Ghana.

A wind ventilated, solar dryer was designed and constructed from locally sourced materials and tested in Nigeria. The dryer was tested on pepper and yam, recording weight losses of 80 % and 55 % respectively. The system achieved a 46.7 % average daylight efficiency. The average drying air temperature in the dryer was higher than the ambient temperature, recording a difference of 5 °C in the early hours of the day to 31 °C at peak (Bolaji, Olayanju et al. 2011).

Hossain, Woods et al. (2007) designed and constructed a mixed mode forced convection solar tunnel dryer for hot red chillies. The dryer achieved a reduction in moisture content of the red chillies from 2.85 kg/kg to 0.05 kg/kg on a dry basis. The findings showed that the drying rate depended on temperature, concluding that at an optimum drying temperature of 65 °C, the optimum airflow velocity achieved was 0.50 m/s; beyond this value the drying rate became independent of air velocity. A drying temperature above 65 ºC had an effect on the colour of the chillies.

2.3.5   Concept of drying

Drying is a critical process in various applications. It involves coupled momentum, heat and mass transfer and can result in physical, chemical and/or biochemical transformations during the drying process (Mujumdar 2006).

2.3.5.1 Moisture in solids

Solids containing moisture can be divided into two distinct categories depending on their behaviour during drying (Henley, Seader et al. 2011):

- Crystalline solids;
- Fibrous and amorphous solids.

Crystalline solids contain pores in their structure to hold moisture; as a result, during drying processes, moisture removal has no effect on the properties of the solid. Fibrous and amorphous solids contain moisture dissolved in the solid, and as a result experience property changes during drying processes.

2.3.5.2 Types of moisture

The moisture in a substance may cause an alteration in the structural, physical and biochemical properties of the substance. These changes may affect the drying process of the substance. Moisture in substances can be grouped into three categories:

- Bound moisture;
- Unbound moisture;
- Free moisture.

Bound moisture is moisture held in the solid, which can be either by biological, chemical and/or physical means. During drying, bound moisture exerts a lower vapour pressure compared to a pure liquid. Unbound moisture is not held to the solid; as a result it is easier to remove than bound moisture and exerts a vapour pressure equal to a pure liquid. Free moisture is moisture contained in a substance in excess of the equilibrium moisture content at a particular temperature and humidity. It can be either bound or unbound to the solid (Treybal 1980).

2.3.5.3 Heat and mass transfer during solar drying

When a substance containing moisture is subjected to drying, heat and mass processes occur simultaneously within the material being dried, in the boundary layer of the solid and the surrounding air. The drying rate is governed by the rate of the transfer processes (Mujumdar 2006).

1. Dual heating of the air and the solid occurs from the solar irradiance. This results in a temperature increase of both the solid and the surrounding air. The temperature rise depends on the intensity of the solar irradiance, the incident surface area of the solid and the airflow rate.

2. Energy transfer from the air to the solid. The moisture removal from the surface of the material occurs by convection. This is dependent on the temperature and humidity of the air, the pressure and airflow rate as well as the external surface area of the solid.

3. Mass transfer occurs in the solid, namely internal mass transfer of the moisture to the surface and external mass transfer to the drying medium. The internal moisture movement is dependent on the morphological characteristics, for example porosity and pore tortuosity, of the solid, internal temperature and moisture concentration. The moisture movement in the solid is affected by liquid diffusion, vapour diffusion, capillary moisture movement and hydrostatic moisture movement mass transfer mechanisms (Mujumdar 2006).

2.3.5.4 Process and material related factors that influence solar drying of FS

Solar drying of agricultural products has been extensively studied, identifying the parameters having an influencing on the drying rate. This is dependent on the rate of moisture diffusion within the material and the rate of moisture evaporation from the surface (Léonard, Vandevenne et al. 2004; Bacelos and Almeida 2011; Doymaz 2007). The moisture diffusion and evaporation rates are dependent on the employed drying conditions. The evaporation rate is influenced by the conditions affecting the external mass transfer properties, such as temperature, relative humidity, air flowrate and the available air-to-material contact surface area (Vega, Fito et al. 2007). The moisture diffusion rates are influenced by the physical composition of the material, internal temperature and the moisture content (Doymaz, Gorel et al. 2004). The incident solar irradiance is critical as it is the driving force of the drying process (Kalogirou 2013).

The temperature difference highly affects the drying rate. Higher temperature means a higher energy input (Bergman, Incropera et al. 2011; Serth 2007). However, excessively high temperatures may cause loss in product quality, alteration of the chemical structure, charring and crusting (Ruiz-López, Córdova et al. 2004, Banga and Singh 1994).

Air at a particular temperature can only hold a specific amount of moisture. The relative humidity of the air affects the amount of additional moisture the air can absorb. The drying rate is dependent on the difference between the equilibrium moisture capacity of the air and the relative humidity of the air. The velocity of the air affects the air circulation in the dryer. An increase in air circulation allows for the removal of more moisture from the system and avoids air saturation (Bergman, Incropera et al. 2011).

The air-to-material surface area influences the available surface area for moisture transfer. An increase in available surface area results in the increase in moisture transfer to the drying medium (Vega, Fito et al. 2007). The available moisture at the surface is in turn affected by the internal moisture transfer to the surface.

The temperature profiles and internal energy in the system for solar drying is dependent on the incident solar irradiance in the system. An increase in solar irradiance intensity results in an increase in the temperature of both the material and the air, resulting in an increase in drying rates (Fudholi, Sopian et al. 2010).

2.3.6   Drying kinetics

Drying kinetics are a representation of the rate of moisture removal from a substance during drying. Drying kinetics are determined experimentally through monitoring of the change in mass against time. There are three experimental methods utilised in the determination of drying kinetics (Kemp, Fyhr et al. 2001):

- Periodic sampling;
- Continuous weighing;
- Intermittent weighing.

Periodic sampling is when part of the sample is taken at constant intervals to monitor the change in moisture content. Continuous weighing is whereby the sample weight is continually recorded throughout the experiment, which can be done through the use of a thermobalance. Intermittent weighing is when, at intervals, the sample is removed from the drying chamber to record the variation in mass.

The drying kinetics can be represented as (Saeed, Sopian et al. 2008):

- Drying curves (mass/moisture content vs. time);

- Drying rate curves (drying rate vs. time);

- Krischer curves (drying rate vs. moisture content).

CHAPTER 3: MATERIALS AND METHODS

This chapter details the characteristics of the FS employed for this study. It describes the custom designed solar thermobalance rig designed for the determination of the drying kinetics. This section also describes the experimental procedure for the determination of the chemical and thermal properties of the sludge before and after solar drying.

3.1   Description of the feedstock, faecal sludge (FS) from VIP latrines

The study was performed on FS from VIP latrines. The sample was obtained during pit emptying within the eThekwini municipality (KwaZulu-Natal, South Africa). The sample was collected in 20 litre-sealed buckets and transported and stored in a cold room at a 4 °C temperature in the Pollution Research Group (PRG) laboratory. The samples had been in storage for a period of between 5 to 6 months before use. An example of sampling procedure is shown in Figure 3-1.

Figure 3-1: Collection of samples during pit emptying

After sampling, the samples were sieved to remove inorganic detritus such as plastics and textiles accumulated through the use of the pit as a disposal option by the user. Sieving was performed using 5 mm and 10 mm grids, starting with the 10 mm to avoid clogging of the sieves. The sieved FS was stored in a closed bucket and returned to the cold room until experimentation.

3.2   Solar thermobalance

A solar thermobalance was required to characterise the drying of FS under solar and open air sun drying. The principle included replication of solar and open air sun drying conditions, including measurements of temperature profiles, mass variations, air profiles and solar irradiance profiles.

3.2.1   Design of the experimental rig

Three conceptual designs were developed: a circular cross-sectional system, a square cross-sectional system and a semi-circular cross-sectional system.

The final design had a frame size with diameter 150 mm and length 400 mm. It had a double wall configuration with either a 5 mm 5-hole input or a singular 5 mm input with a 75 mm outlet. It had a vacuum space with an outer 200 mm diameter and an inner 160 mm diameter. It was made from acrylic glass with PVC covers. The melting points of acrylic glass and PVC covers are 160 °C and 140 °C respectively. The safe operating temperature was a maximum of 90 °C at which point the acrylic begins to deteriorate. Full drying rig drawings are available in Appendix B.

3.2.2   Air flow computational simulation model

Computational fluid dynamics (CFD) analysis is used to simulate fluid flow mechanics models to test for feasibility and ensure design success, providing insight into the expected results and performance of the system when in use. The solar drying prototype used air as the heat transfer medium as well as for moisture removal, allowing for the generation of flow through the drying system. A CFD analysis was carried out to simulate the flow processes of the prototype at various flowrates for optimum drying performance. Four different simulation models were applied:

- Multi-inlet with diffuser plate
- Multi-inlet without diffuser plate
- Singular inlet with diffuser plate
- Singular inlet without diffuser plate

The general model information utilised a standard variable air inlet system, as the end of the drying chamber was exposed to environmental conditions of temperature and pressure, so outlet conditions were treated as atmospheric. The final CFD models utilised on average 117 442 full fluid cells, 224 714 partial cells and the average simulation run time was 2 917 seconds.

In the model development, it was assumed that constant flow rates were provided to the inlet valves. The flow was considered a constant density gas, with no significant change in properties. Due to the expected flow conditions, the flow was modelled as fully developed turbulent flow. It was assumed there would be no expansion of the gas through the drying chamber due to temperature change. K-Epsilon turbulence models were employed with a realisable two-layer treatment and it was selected as it performs best for wall y + values less than 300.

An internal analysis, which excluded cavities without flow conditions, with the fixed feature of a diffuser plate, was implemented. For the flow analysis, thermodynamic conditions were considered to be at room temperature, with no pre-set velocity parameters. Mesh resolution was set to 6, as this was a good compromise between mesh quality and computational time. A solid standard mesh type was applied. SI units were implemented.

Figure 3-2: CFD simulation of the drying chamber with singular inlet without diffuser plate results

Figure 3-2 shows the results of applying a singular inlet flow system. The results show that there is a low loss in pressure across the system highlighted by the continued flow with minimal reduction in flow velocity. The results also show that although flow is generated in the system, there is a high flow rate in a thin strip at the centre of the prototype without much spread of the flow. Little flow is generated closer to the walls of the prototype.

Figure 3-3: CFD simulation of the drying chamber with singular inlet with diffuser plate results

Figure 3-3 shows the effects of applying a diffuser plate to a singular air flow inlet system. The results show that the diffuser plate generates a spread in flow, but it also results in a generation of a high back pressure, resulting in a very low flow rate across the prototype. The flow is spread greatly over the cross-sectional surface area. Use of the diffuser plate restricts the maximum achievable flow rate as even high volume inlet values result in low flow rates as the back pressure generated by the diffuser plate reduces the inlet volume flow to maintain continuity, i.e. volume of air entering the system is equal to volume of air exiting the system.

Figure 3-4: CFD simulation of the drying chamber with multi-inlet with diffuser plate results

Figure 3-4 shows the results of applying the diffuser plate with a multi-inlet flow system. The diffuser plate enhances the spread of the flow. But the back pressure generated reduces the cross-sectional flow rate through the system.
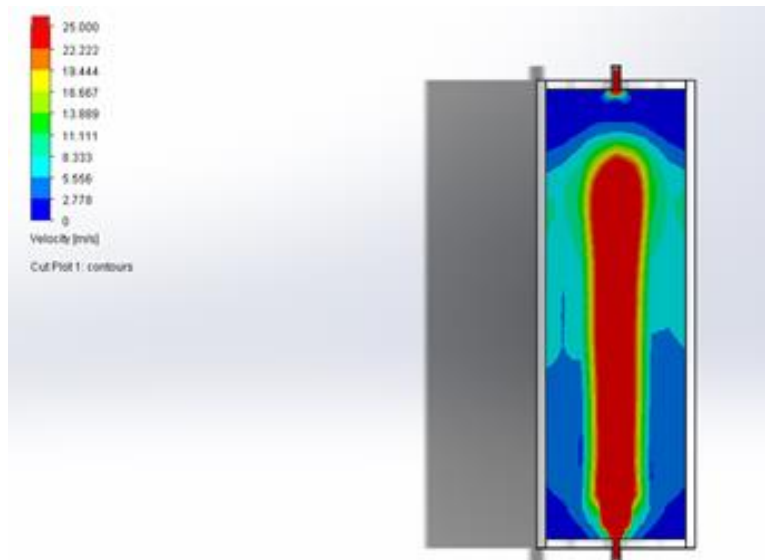

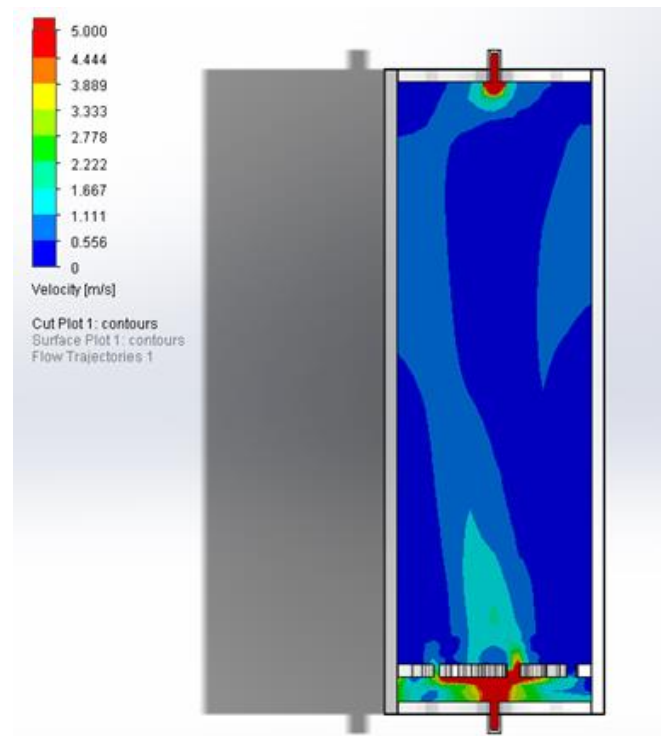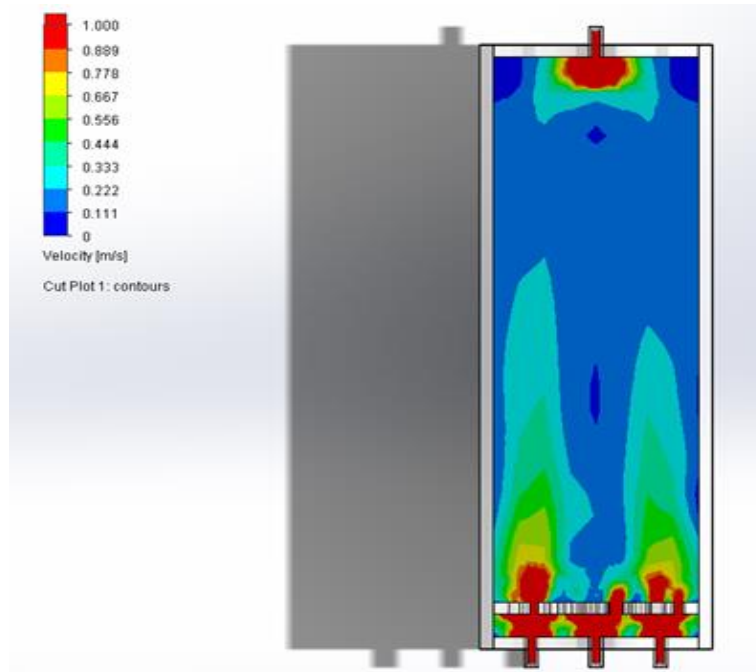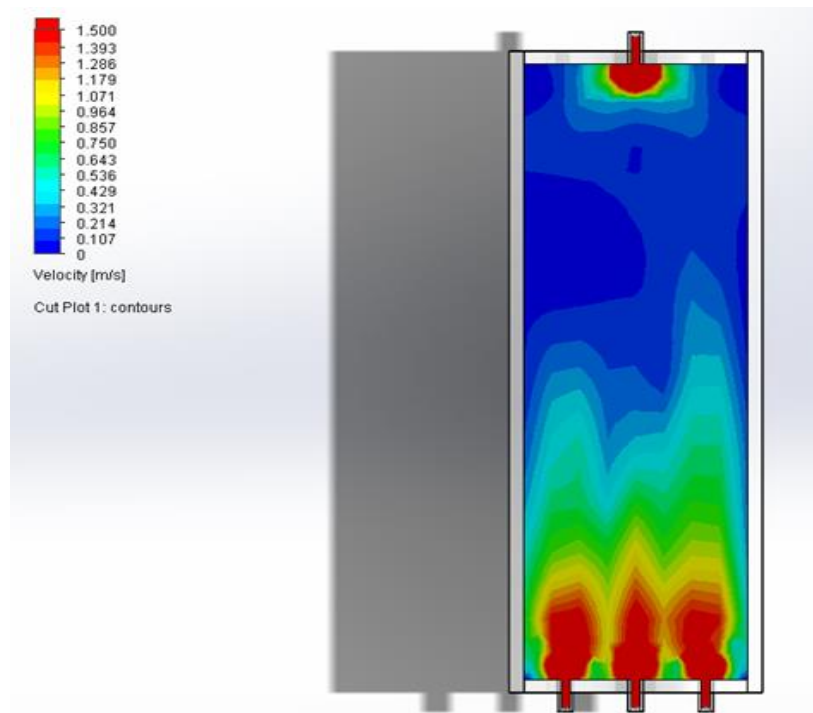**Figure 3-5: CFD simulation of the drying chamber with multi-inlet without diffuser plate results**

Figure 3-5 shows the results of applying the multi-inlet airflow system without a diffuser plate. The results demonstrate that dividing the inlet volume over a series of inlets enhances the distribution of the flow. The inlets have a fairly low distribution but the general flow characteristics over the cross-sectional area are more defined and the required inlet flow rates are better achieved in these conditions. The pressure drop across the prototype is low, as a result there is continuous flow. The flow narrows in the last 100 mm of the end to converge and exit the system.

The final prototype utilised a 5-way multi-inlet system. It also has inlet options for the temperature sensors, humidity sensors and the mass balance. The temperature sensors were situated at the inlet and outlet end of the prototype. It also applied a vacuum casing as insulation to minimise the heat loss through radiation. As a result the prototype was double layered. It was made from acrylic glass due to the ease in machining and its physical properties.

3.2.3   Description of the solar thermobalance

A solar drying rig with a thermobalance was used for the drying experiments. The testing rig was located on the roof of the chemical engineering building at the Howard College campus of the University of KwaZulu-Natal (latitude: 29°52'08.1" S; longitude: 30°58'46.6"E). The drying system can be classified as a direct solar drying system as the heat energy is provided by direct solar irradiance. The system can be categorised into three separate sections, which are:

- Air pre-heating section;
- Drying section;
- Control and monitoring section.

The airflow was supplied by a compressed air line. The air stream was firstly directed to an air flowmeter to measure and regulate the flowrate. The flowmeter was previously calibrated in the range of the required flowrates in the drying chamber. The air stream was then directed to the heating system where applicable, i.e. experiments that required air pre-heating, or to the flow divider. The system utilised a multi-entry inlet, with the flow divider being a custom built device designed to separate the singular inlet air flow into 5 streams (as shown in the simulations). The heating system was comprised of a trio of heating coils with a PT100 temperature sensor connected to the exit pipe with a feedback loop system to control the required temperature at the output. A humidity meter was also connected at the inlet and exit of the drying chamber.

After the heating system, the flow was directed to the flow divider before entering the drying chamber though the multi-entry inlet. The drying chamber is where the FS samples were dried. The drying chamber also included two inlet ports apart from the air inlets and exit; these were for the temperature measurements and the mass reading. Temperature measurements were done inside the drying chamber, in the ambient air, at the core and surface of the sample. A thermocouple was included at the exit of the drying chamber. The mass balance had an accuracy of 0.01 g and was connected to a data logging system to record the variation in mass with time. The sample was placed on a support connected to the balance.

A pyranometer was also included in the system to measure solar irradiance at the site. The pyranometer was placed at a distance of 1 m away from the FS sample and it recorded the global horizontal irradiance (GHI). GHI is a combination of the direct irradiance normal to the incident surface and the diffused irradiance that is received at a particular place parallel to the earth's surface.

A control and monitoring system was developed for the system. The system recorded the different measurements and was used to monitor and control the system. The system comprised a data logger, amp box and power regulators. The amp box was used in conjunction with the pyranometer for reading of solar data. The control and monitoring system was used to power on and off the various pieces of equipment. A connection was developed between the control system and the computer to monitor performance of the system, record the data and adjust parameters where necessary. Temperature, airflow velocity, relative humidity, solar irradiance and sample mass were constantly monitored and the values from the measurements were continually logged on an MS Excel spreadsheet. Figure 3-6 and Figure 3-7 show the user output interface and the control system.
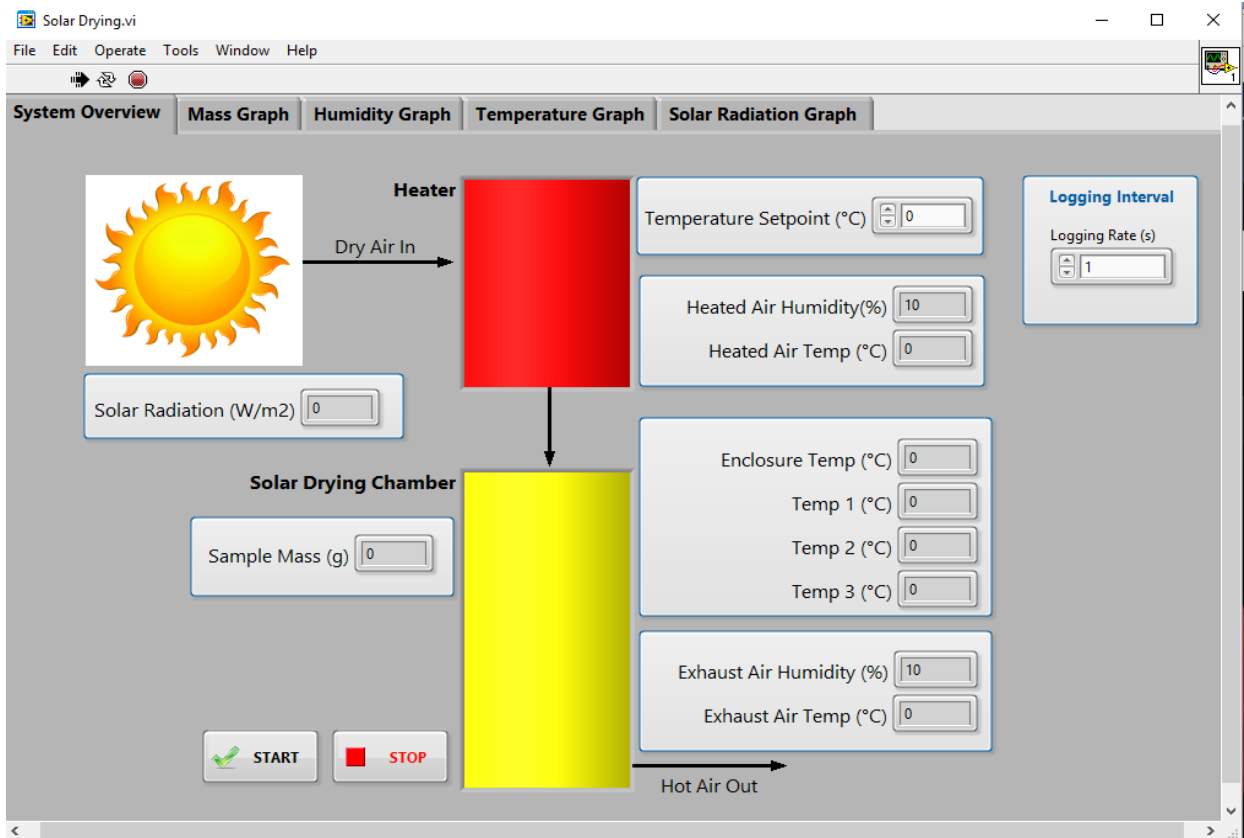
Figure 3-6: Control system computer interface

Figure 3-7: Control system

Figure 3-8 and Figure 3-9 show the schematic flow chart of the solar drying rig and a photograph of the solar drying rig set-up.
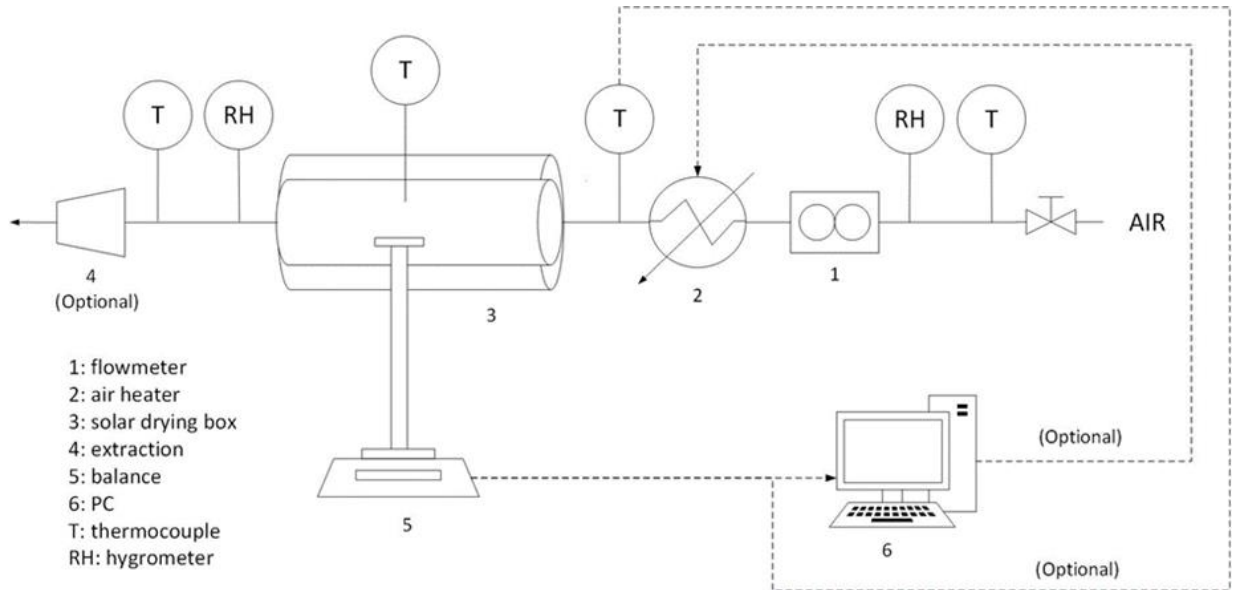

Figure 3-8: Flow chart schematic of solar drying rig

Figure 3-9: Solar drying rig set-up

3.3 Experimental procedure

Unless stated otherwise, the experimental procedures were performed in accordance with the standard operating procedures detailed and reproduced in Appendix C and in the operations manual which can also be accessed on the website of the Pollution Research Group (http://prg.ukzn.ac.za/laboratory-facilities/standard-operating-procedures).

3.3.1 Operating conditions

The following drying conditions were investigated:

Weather conditions - The effect of the weather conditions - sunny, cloudy and overcast - were investigated without air preheating, with an airflow velocity of 0.5 m/s, for a sample of 5 mm thick and 60 mm surface diameter.

Air preheating temperature - Experiments with air preheating temperature at 30 °C and 60 °C, as well as no pre-heating, were carried out in sunny conditions, while keeping the airflow velocity at 0.5 m/s, for a sample of 5 mm thick and 60 mm surface diameter.

Airflow velocity - Experiments without air introduction (but with an assumed natural convection flow) and with air introduction at a velocity of 0.5 m/s and 1.0 m/s, were conducted in sunny conditions, without air preheating, for a sample of 5 mm thick and 60 mm diameter. Note that the air velocity refers to the velocity at the location of the sample, measured through the use of an anemometer.

Thickness - The effect of thicknesses of 5 mm and 10 mm were investigated in sunny conditions, while applying no air preheating at an airflow velocity of 0.5 m/s, for a sample of 60 mm surface diameter.

Surface area - The effect of the surface area were investigated with samples of different diameters (60 and 120 mm) and 5 mm thickness, in sunny conditions, while applying no air preheating at an airflow velocity of 0.5 m/s.

Each experiment was done in replicates for each set of drying experimental conditions. Dual experiments for open air sun and solar drying were carried out simultaneously. The experiments were conducted in spring, during the months of October and November. Table 3-1 shows the summary of the investigated drying conditions.

Table 3-1: Summary of drying conditions

Drying conditions	Variations		
Weather conditions	Sunny	Cloudy	Overcast
Air preheating	No preheat	30 °C	60 °C
Airflow velocity	Natural convection	0.5 m/s	1.0 m/s
Sample thickness	5 mm	10 mm	-
Cross-sectional surface diameter	60 mm	120 mm	-

3.3.2 Sample and experimental preparation

The effect of solar drying was tested by means of a thin layer of FS. Before the use of the sludge for experimentation, it was mixed in a bucket with a mixing rod to ensure homogeneity.

Various diameter and height petri-dishes were utilised. FS was placed on the appropriate crucible with the required dimensions. The average mass of sludge before the beginning of the experiment was between 20 g to 50 g ± 1 g.

Prior to the start of the solar drying experiments, the solar thermobalance was run for 15 minutes ± 5 minutes so as to ensure that steady operating conditions were achieved. During the experiment, the mass, temperature, relative humidity and solar irradiance were recorded at 1 minute intervals during the solar drying experiments. For the open air sun dried samples, the sample mass was manually recorded every 30 minutes through the use of a mass balance and both the experiments, solar drying and open air-sun drying, were run for an equal amount of time, from 10:00 am to 4:00 pm ± 15 minutes.

Two thermocouple thermometers were inserted into the sludge, one slightly under the surface and the second deep into the sludge to measure surface and core temperatures respectively. A further two thermocouple thermometers were placed inside the drying camber about 5-6cm above the sludge in the test camber and one above the open air dried sample, to measure drying chamber and ambient air temperatures respectively.

3.4 Characterisation of the dried sludge

Characterisation of the samples was performed to determine the effect of solar thermal drying on the physicochemical properties of the sludge. Each analysis was performed on the wet and dried samples to determine the effects of the solar drying on the quantitative and qualitative aspects and included replicates in order to determine the uncertainty of the measurement. Table 3-2 shows the summary of the quantitative and qualitative properties analysed.

Table 3-2: Summary of characterisation tests of the dried FS categorised into quantitative properties and qualitative observations

QUANTITATIVE PROPERTIES	Physical	Moisture content	Ash content	Shrinkage	Density
	Thermal	Calorific values	Heat capacity	Thermal conductivity	-
	Elemental nutrients	Carbon	Nitrogen	Sulphur	-
	Molecular nutrients	Ammonium	Nitrates	Orthophosphates	-
QUALITATIVE OBSERVATIONS		Crusts	Cracks	Visual aspects	Odour

3.4.1 Quantitative properties

Moisture content

Moisture content was determined by placing the samples in ceramic crucibles and drying the samples in an oven at 105 °C for a minimum period of 24 h. The moisture content (M) can then be defined in either a dry (*db* in index) or wet basis (*wb* in index). The moisture content is defined by equations (3-1) in dry basis, and (3-2) in wet basis.

$$\%M_{db} = \frac{w_0 - w_f}{w_f} \times 100\% \qquad (3\text{-}1)$$

$$\%M_{wb} = \frac{w_0 - w_f}{w_0} \times 100\% \qquad (3\text{-}2)$$

Where: w_o is the initial mass of the sample before being oven dried.

w_f is the dried mass of the sample.

The moisture content in wet and dry basis are related by equation (3-3):

$$\% M_{db} = \frac{M_{wb}}{100 - M_{wb}} \times 100\%$$
(3-3)

The average moisture content of the wet FS used in this study was found to be 78% in wet basis (355% dry basis).

Ash content

Ash content is the amount of material that remains after combustion of the FS in an oven at 550 °C for 2 hours (for VIP FS samples). It represents then the inorganic material that remains after the removal of all water and organic matter components by combustion. It is calculated by equation (3-4).

$$Ash\,content = \frac{w_f - w_{f2}}{w_f} \times 100\%$$
(3-4)

Where: w_{f2} is the mass of material residue after combustion.

The average ash content of the wet FS used in this study was found to be 0.474 g/g dry sample.

Thermal analysis of faecal sludge (FS)

The characterisation of the thermal properties of the sample is relevant for the thermal treatment processes of FS and the determination of the potential of resource recovery from the dried product. The thermal properties analysed were calorific values, heat capacity and thermal conductivity. The calorific values was determined by combusting a pre-weighed known mass of FS in an oxygen bomb calorimeter (*Parr 6200*). Both the thermal conductivity and heat capacity were determined using a thermal conductivity analyser (*C-Therm TCi*) which uses the modified transient plane source (MTPS) technique in describing the thermal conductivity and heat capacity of materials.

Nutrient analysis

Nutrient analyses were performed on the dried product in order to ascertain the effect of solar drying on the agricultural value of the sludge as a nutrient supplement or/and soil conditioner. The nutrients that were investigated can be split into two categories, which are elemental and molecular nutrients. The elemental nutrients include carbon (C), nitrogen (N) and sulphur (S). The concentration of these nutrients in sludge were determined using a microwave plasma-atomic emission spectrometer *(4200 MP-AES)* equipped with a concentric nebuliser.

The molecular nutrients investigated were ammonium (NH_4^+), nitrates (NO_3^-) and orthophosphates (PO_4^{-3}). A Spectroquant photometer (*Pharo 300*) and the relevant commercial test kits specific to the analysis were utilised to determine the concentrations of the molecular nutrients. Prior to each test, a known mass of the sample was added to a known volume of water and centrifuged for liquid-solid separation. The resultant liquid was taken and analysed.

Density

The effect of drying on the density of the sludge was investigated. The average height of sample values were recorded using a ruler calibrated in millimetres before and after drying for each experiment so that the volume properties of the sample could be attained. The mass of the sample was measured using a mass balance, with an accuracy or 0.0001 g.

$$\rho = \frac{m}{V} = \frac{m}{\pi r^2 h} \qquad\qquad (3\text{-}5)$$

Where: ρ is the density of the material

m is the mass of the sample

V is the volume of the sample

r is the radius of the petri-dish

h is the height of the sample

Shrinkage

Shrinkage was measured in proportion to the initial volume. This was physically calculated using the measurements for the initial and final volume after experimentation on the samples.

$$Shrinkage = \frac{V_f}{V_i} = \frac{\pi r^2 h_f}{\pi r^2 h_i}$$ (3-6)

Where: V_f is the final volume of the sample, h_f is the final height of the sample

V_i is the initial volume of the sample, h_i is the initial height of the sample

3.4.2   Qualitative observations

Crust

Crusting of the surface is a common occurrence in drying. Formation of crusts hinder mass transfer off the surface of the water and hence affect drying rates. A qualitative look through visual observation and crust feel on crust formation was carried out on both samples, for open air sun and solar drying.

Cracks

Cracks can form on hard surfaces, thus during drying, formation of crusts could be coupled with cracks. Cracks are positive for the mass transfer and so they are desirable when there is crust formation. A visual observation at crack formation was carried out on both samples, open air sun and solar drying.

Colour

Quality of dried produce is concerned with the colour and visual aspects of the samples. These were made as a relative comparison of the before and after aspects.

Odour

The odour of FS directly influences the acceptance of FS by communities. A qualitative analysis of the odour strength was carried out before and after experimentation on all samples. This was done by smell in order to compare the odour emission before and after drying.

3.5   Data analysis

Mass ratio

The mass ratio is the ratio of the mass of the sample at a particular time to the initial mass. It is calculated using equation (3-5):

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad \text{(3-5)}$$

Where: MR - mass ratio

M - mass of the sample at any particular instance

M_o - initial mass of the sample

M_e - mass at the equilibrium moisture content

The moisture content of the drying material which is in equilibrium with the amount of moisture contained in the drying agent at a given temperature and humidity, is known as the equilibrium moisture content (M_e). In theory, a material cannot be dried to a moisture content below the applicable equilibrium moisture content. M_e can be considered a constant for solar drying, equation (3-5), can be adjusted to equation (3-6)

$$MR = \frac{M}{M_o} \qquad \text{(3-6)}$$

Drying rate

The sample mass was constantly monitored and the results continually logged onto the computer using a data logging system coupled with an MS Excel package. The amount of evaporated moisture loss over time and per surface area unit, the drying rate, was calculated by dividing the change in mass of the sample by the time as shown in equation (3-7). Average drying rates were utilised for experimental performance comparison.

$$Drying\ rate = \frac{w_t - w_{t+\Delta t}}{\Delta t.A} \qquad \text{(3-7)}$$

CHAPTER 4: RESULTS AND DISCUSSION

This section presents and discusses the results from the experimental work conducted on the solar drying of FS from VIP latrines. This chapter is divided into 3 main sections. The first section details the effect of varying the weather conditions, air preheating, air flowrates, sample thickness and surface area on the drying kinetics of FS. It also exhibits the measurements of temperature at different locations in the experimental setup and in the sample and the solar irradiance. The second section details the effects of the drying conditions on the properties of the FS. The properties analysed included physical properties, thermal properties and nutrient content, as these are critical for the reuse of the dried FS. The third section looks at the qualitative observations of the sludge transformation after drying. The properties analysed included crust formation, crack formation and odour analysis as these influence the drying process (crust and crack formation) and social acceptance for the reuse of FS (odours). .

4.1 Drying kinetics

This section shows the drying curves obtained during the solar drying experiments so as to ascertain the effect of the parameters that were investigated. The parameters investigated were weather conditions, open-air sun drying, airflow velocity, air preheating, sample thickness and surface area. The drying curves were presented as mass ratio variation against time.

Unless stated otherwise, the results detailed in this section are of a flat geometry at a surface area of 60mm diameter and 5mm thickness. Particular focus was placed on a flat geometry set-up as it is the currently applied method in use, for example in drying beds and the BSFL plant in Isipingo. A control set-up was also used to compare solar drying to sun drying. The replications of the drying curves are available in Appendix D.

4.1.1 Effect of weather conditions

The solar drying and open air sun drying is influenced by the intensity and availability of sunlight, which depends on the weather conditions. The effect of the weather on the solar drying of FS was investigated on sunny, cloudy and overcast conditions.
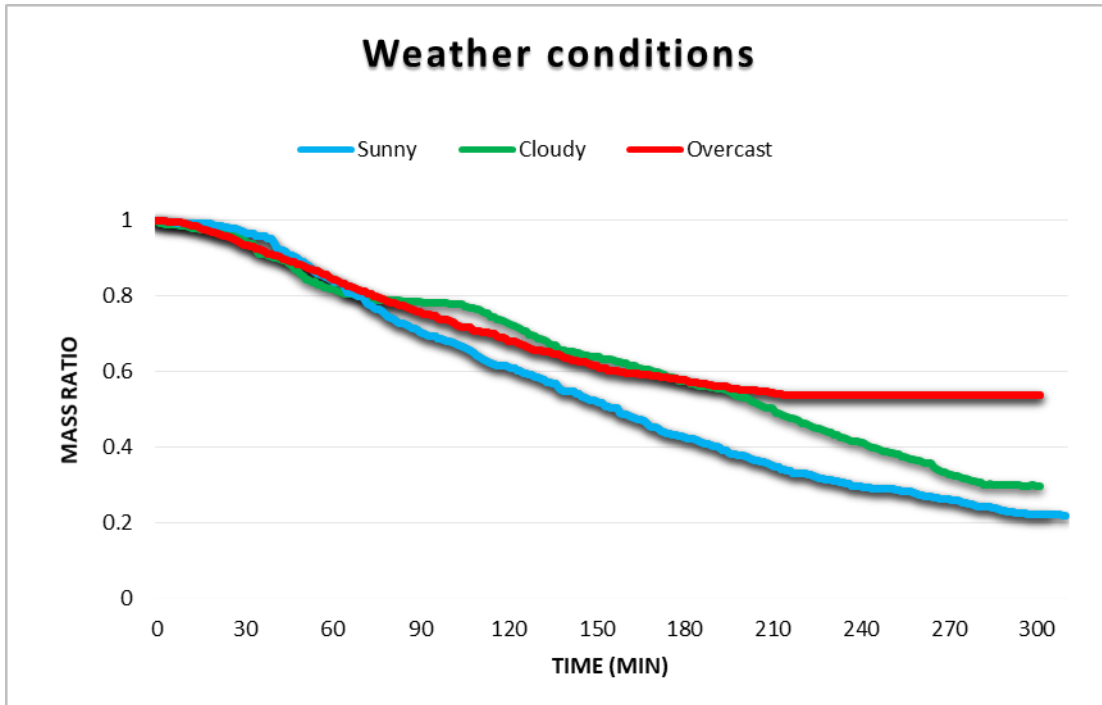
Figure 4-1: Mass ratio variation as a function of time during the solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny, cloudy and overcast conditions
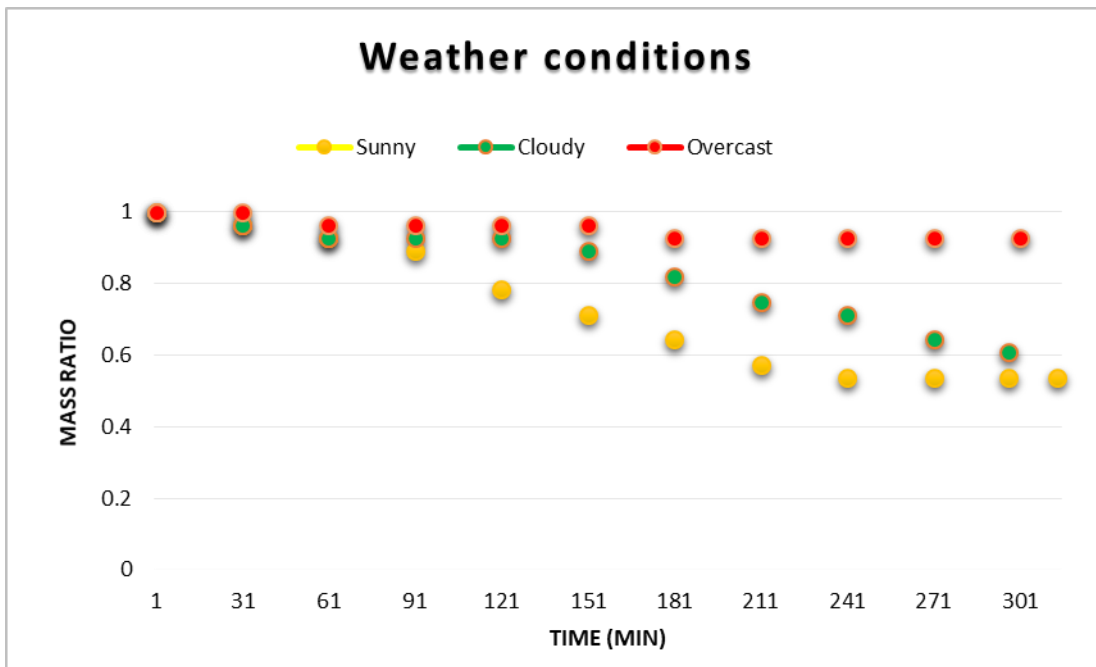

Figure 4-2: Mass ratio variation as a function of time during the open air sun drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny, cloudy and overcast conditions

Figure 4-1 and Figure 4-2 show the drying curves depicting the variation of the mass ratio at different weather conditions for open-air sun drying and solar drying respectively. Sun drying varies for a final mass ratio of 0.54, 0.56 and 0.97 for sunny, cloudy and overcast conditions respectively. Solar drying values vary for final mass ratios of 0.20, 0.25 and 0.55 for sunny cloudy and overcast conditions respectively.

Drying FS in sunny conditions presented a lower final mass ratio, closely followed by cloudy conditions. The drying rates followed a similar trend with the sunny conditions having the highest drying rate, followed by cloudy conditions. A notable difference was observed for overcast conditions with respect to sunny and cloudy conditions, where sun drying led to a lower mass reduction and drying rate, particularly for open-air drying.
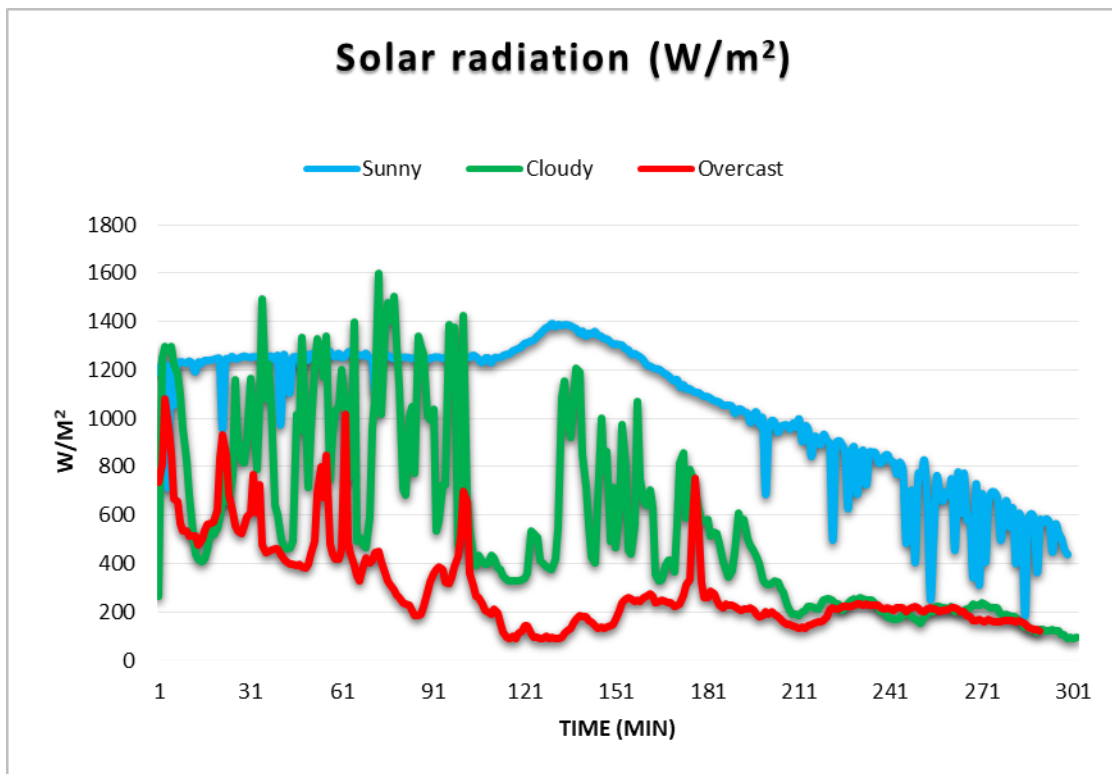

Figure 4-3: Sunny, cloudy and overcast conditions solar irradiance at the site and test period

Figure 4-3 shows the solar irradiance received for the different weather conditions with an average of 1 100 W/m², 950 W/m² and 300 W/m², for sunny, cloudy and overcast conditions respectively. There was a minimal difference between sunny and cloudy conditions, but there was a vast difference with overcast conditions. The results also showed the dependence of the drying kinetics

on the solar irradiance as sunny and cloudy conditions received high irradiance values resulting in higher drying rates and a lower final mass ratio.
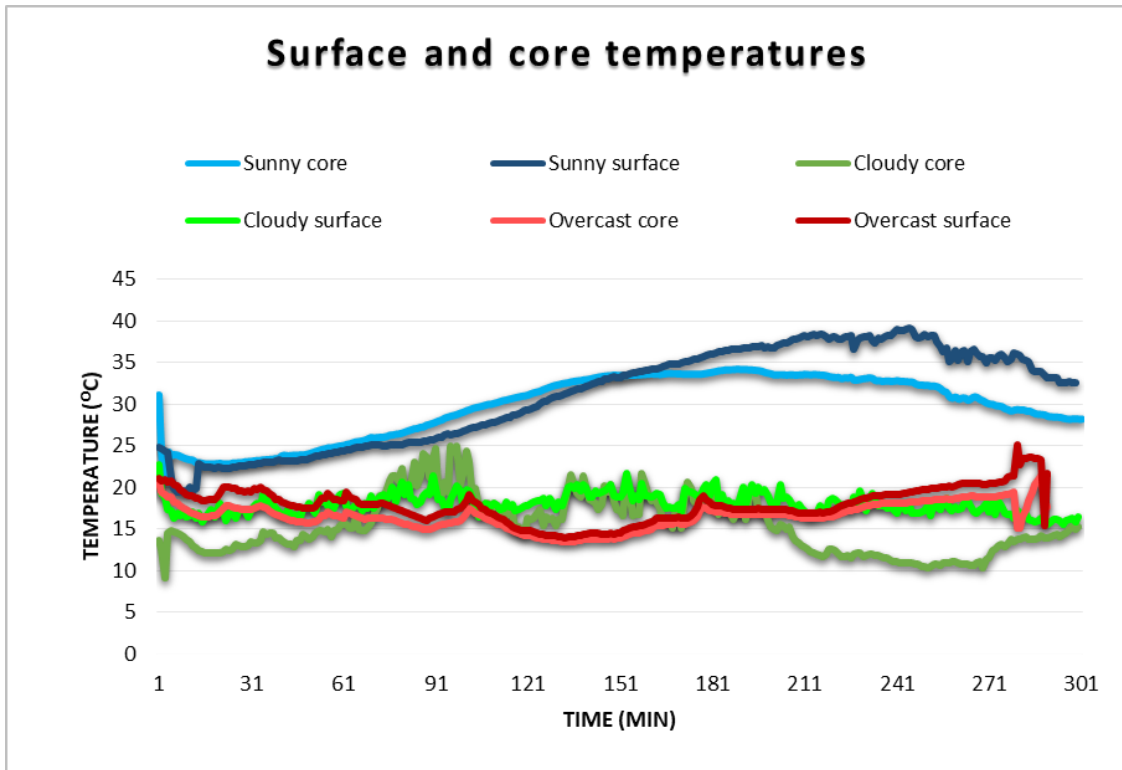

Figure 4-4: Surface and core temperatures at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny, cloudy and overcast conditions
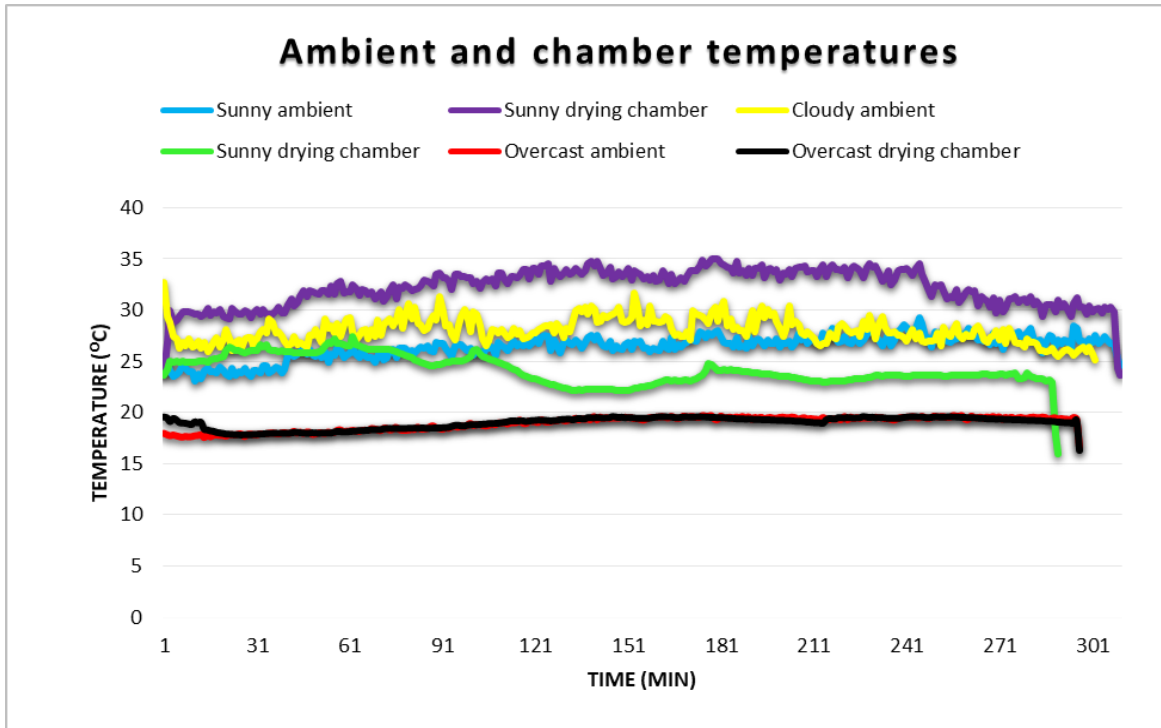
Figure 4-5: Ambient and chamber temperatures at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny, cloudy and overcast conditions

Figure 4-4 and Figure 4-5 compares the drying chamber temperature, sample core and surface temperature, and the ambient temperatures at the different conditions. The sunny conditions temperatures were consistently high, with overcast temperatures constantly low and cloudy conditions fluctuating. This is due to sunny and overcast conditions having fairly consistent solar energy irradiance. Cloudy conditions fluctuated as a result of experiencing alternating sunny solar exposure and cloud cover. Chamber/drying temperatures were consistently higher than ambient temperatures, this was due to the greenhouse effect of the enclosure, highlighting the effectiveness of solar collection; overcast conditions showed no difference, with the difference of approximately 8 °C in ambient and chamber temperatures recorded in sunny conditions. No heated air was introduced to the drying chamber during these tests. Cloudy conditions fluctuated in-between.

The results show an average drying rate of 0.686 kg/h.m^2, 0.606 kg/h.m^2 and 0.078 kg/h.m^2 for sun drying compared to an average of 1.066 kg/h.m^2, 0.944 kg/h.m^2 and 0.622 kg/h.m^2 for solar drying in sunny, cloudy and overcast conditions for the average solar irradiance of 1 100 W/m^2, 950 W/m^2 and 300 W/m^2 respectively.

4.1.2 Comparison of open air sun drying and solar drying

Open air sun drying refers to the exposure of the sample to direct sunlight without enclosure, whereas solar drying occurs in the drying chamber with a controlled environment (Adair 1985). Figure 4-6, Figure 4-7 and Figure 4-8 shows the comparison between solar drying and open-air sun drying under varying weather conditions – sunny, cloudy and overcast respectively. The results show that solar drying has better performance capabilities in each case, with a final mass ratio difference of 0.35, 0.30 and 0.45 for sunny, cloudy and overcast conditions respectively.
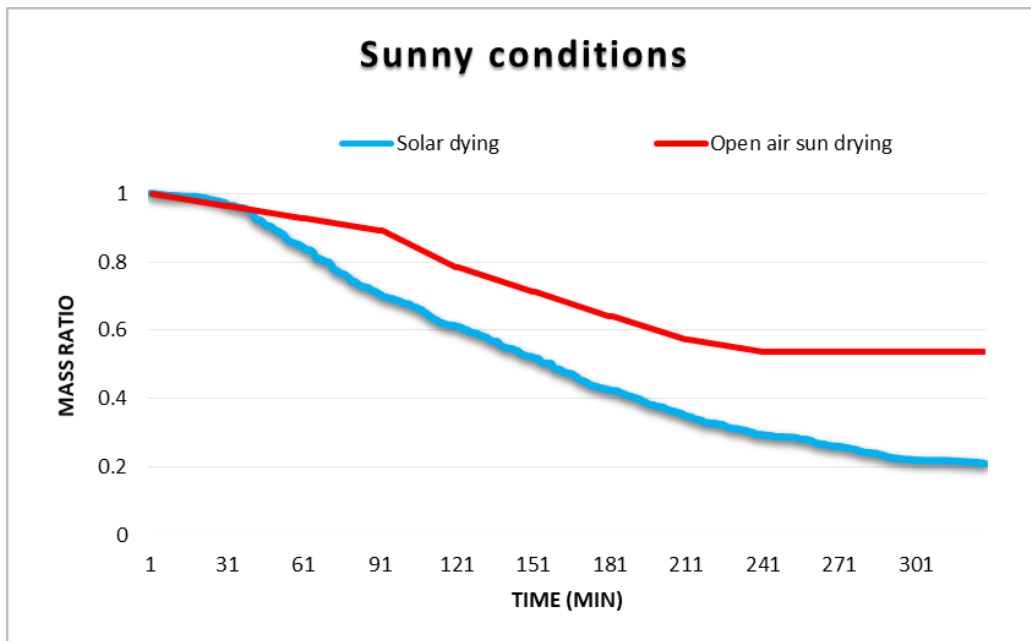

Figure 4-6: Mass ratio variation as a function of time during the open air sun and solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions
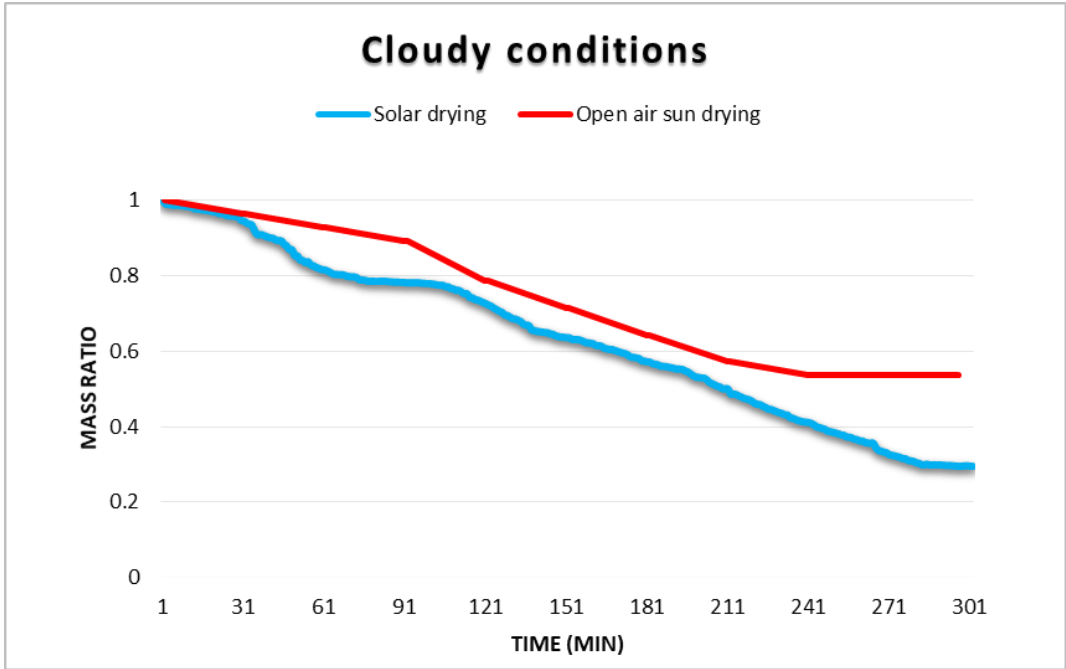
Figure 4-7: Mass ratio variation as a function of time during the open air sun and solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under cloudy conditions
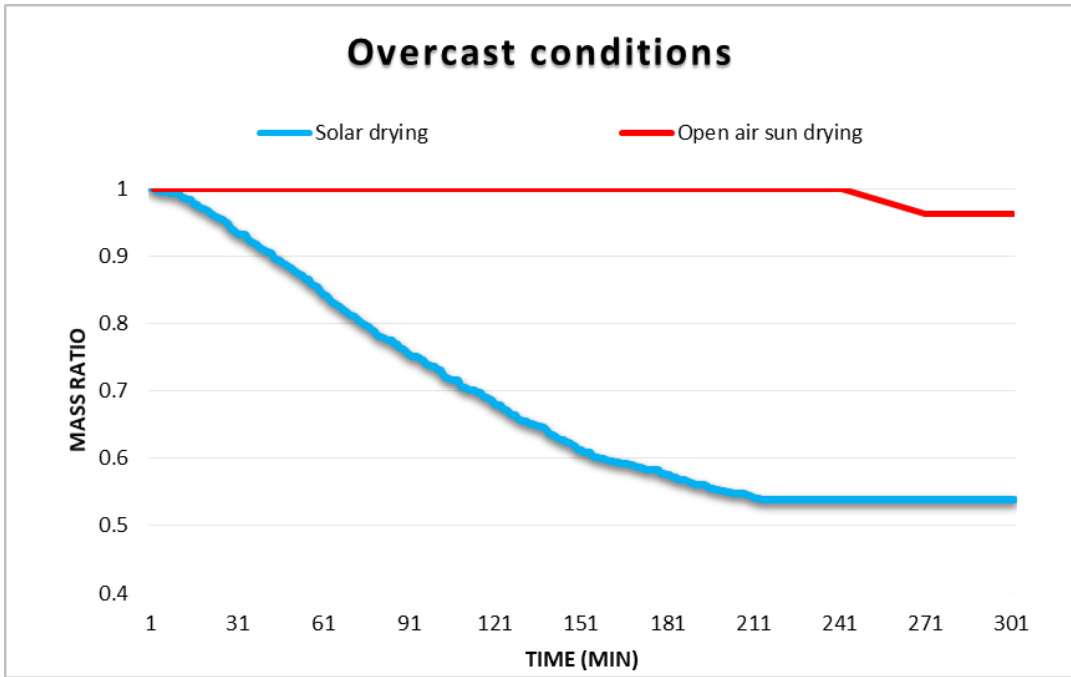

Figure 4-8: Mass ratio variation as a function of time during the open air sun and solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under overcast conditions

4.1.3   Effect of thickness

The thickness of the sample affects the heat and mass transfer properties of the FS. Indeed, the moisture has to be transferred from the core of the sample to the surface and the transfer time is dependent on the distance to be covered. The same applies to the transfer of the energy from the surface of the sample to the core. The effect of the thickness on the solar and sun drying of FS was investigated by varying the thickness.
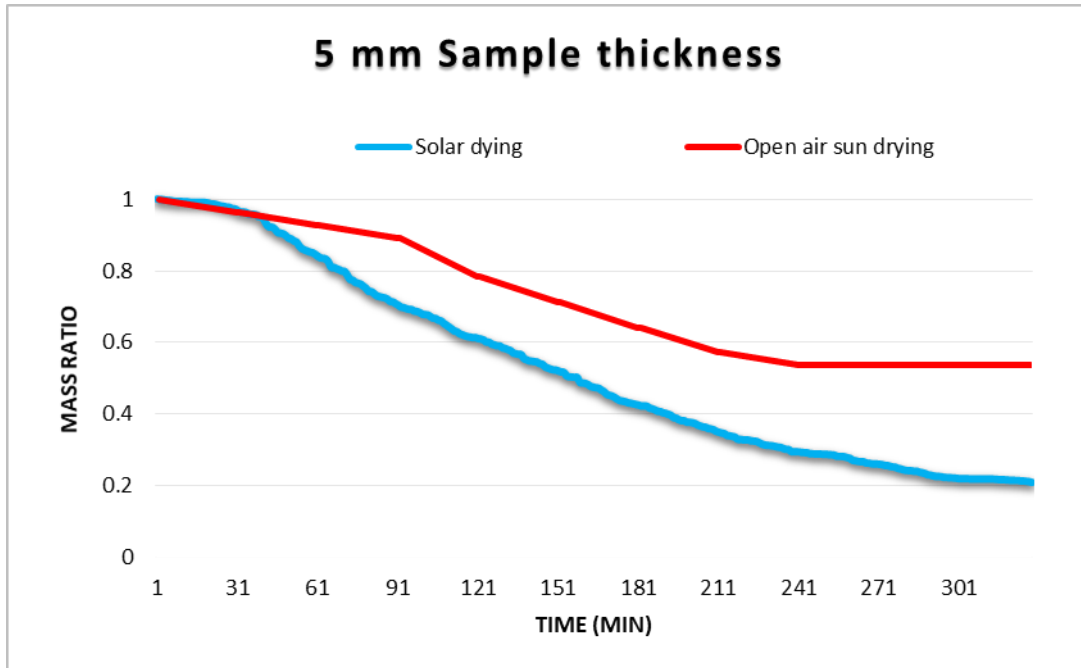

Figure 4-9: Mass ratio variation as a function of time during the open air sun drying and solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions
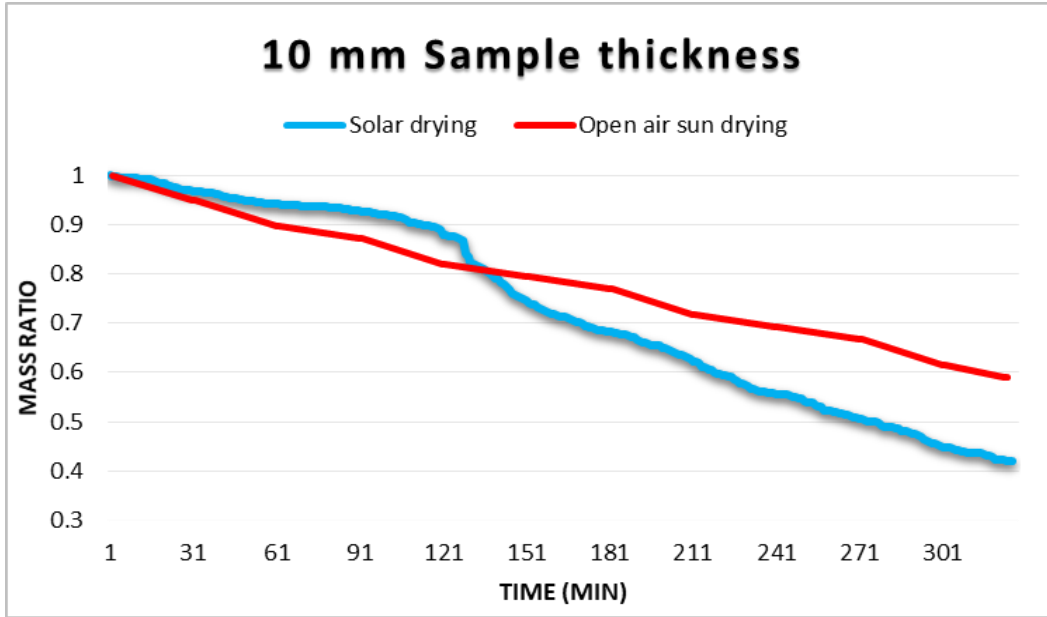
Figure 4-10: Mass ratio variation as a function of time during the open air sun drying and solar drying of FS at 60 mm cross-sectional surface diameter, 10 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-9 and Figure 4-10 compare the drying kinetics of the 5 mm and 10 mm solar and sun drying kinetics respectively. As expected, solar drying presented a better performance with a difference of 0.35 and 0.25 for the 5 mm and 10 mm samples with respect to open-air drying, respectively.
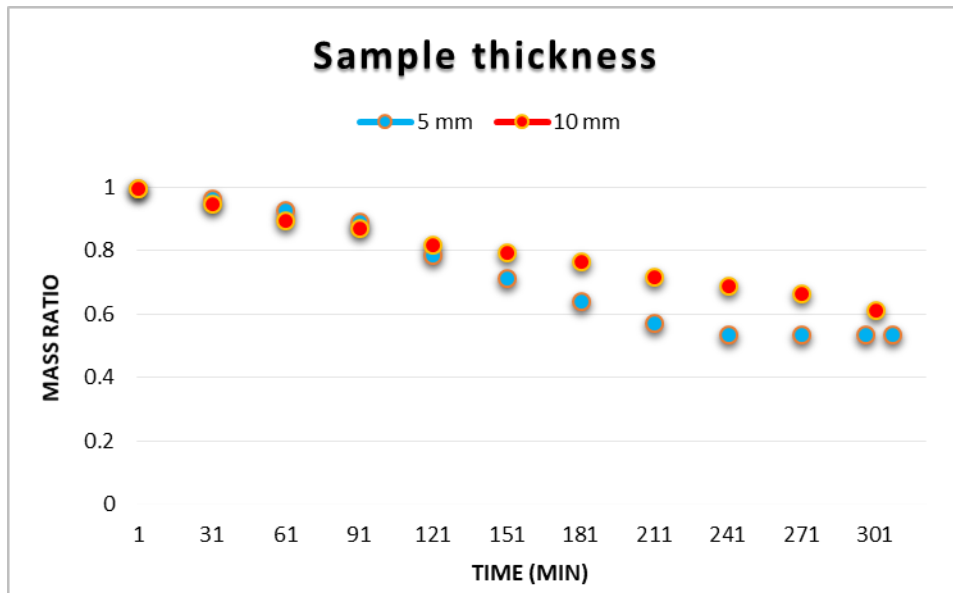

Figure 4-11: Mass ratio variation as a function of time during the open air sun drying of FS at 60 mm cross-sectional surface diameter, 5 mm and 10 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-11 compares the drying curves for the open air sun dried samples. The final mass ratios were 0.50 and 0.55 for the 5 mm and 10 mm samples respectively. This showed an average drying rate of 0.616 kg/h.m^2 and 0.686 kg/h.m^2 respectively. The results showed similar drying rates from 5 mm to 10 mm thickness.
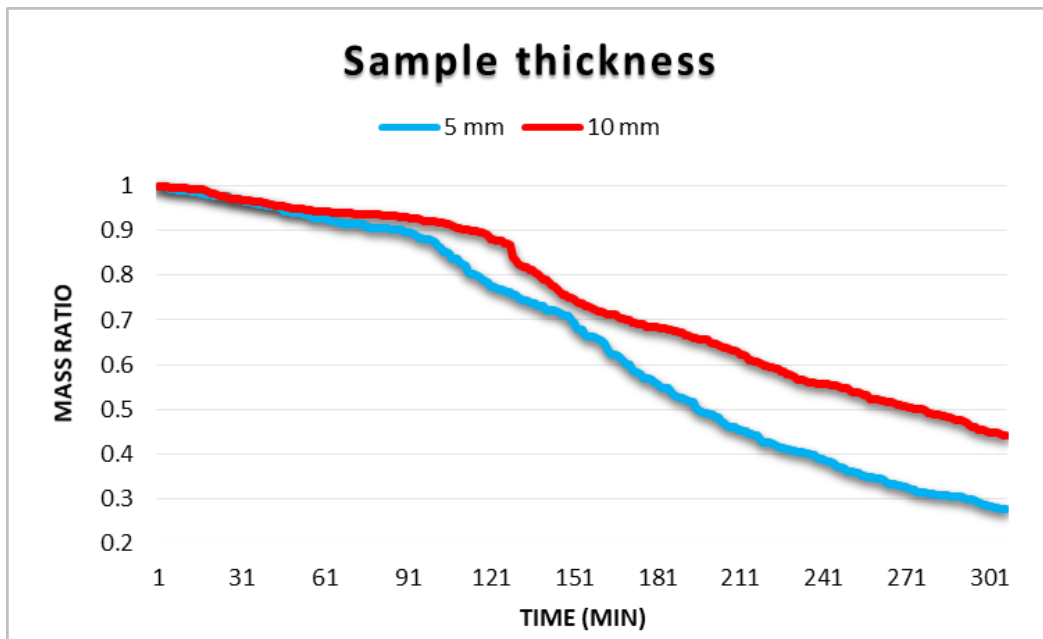

Figure 4-12: Mass ratio variation as a function of time during the solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm and 10 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-12 compares the drying curves for the solar dried samples. The final mass ratios achieved were 0.21 and 0.45 for the 5 mm and 10 mm samples respectively. The average drying rates were 1.066 kg/h.m^2 and 1.371 kg/h.m^2 respectively, highlighting an improvement in the overall moisture quantity lost with the increase in sample thickness.
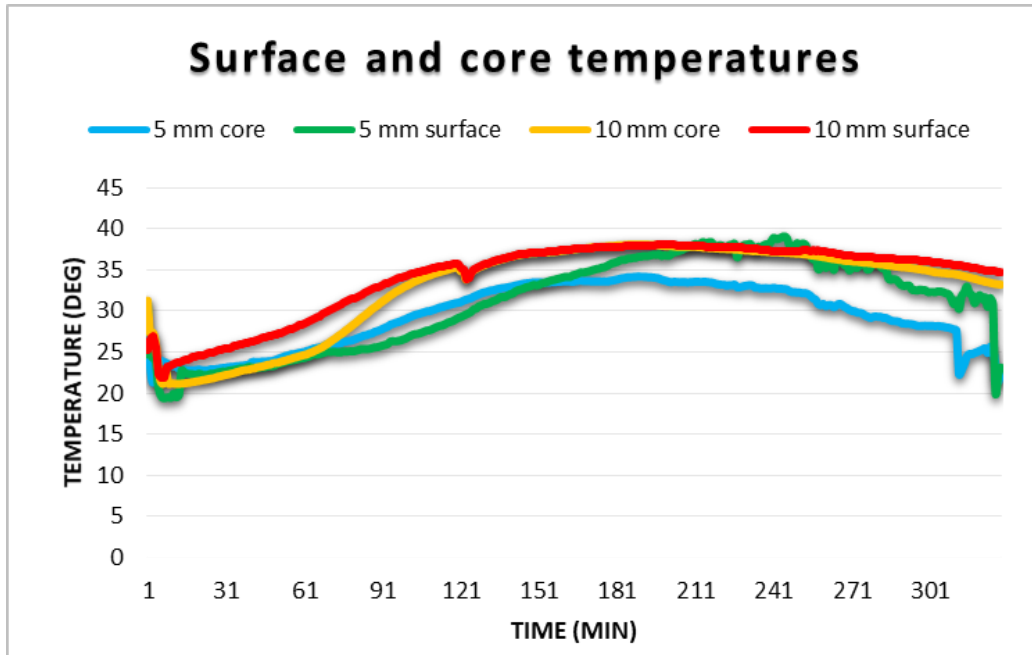
Figure 4-13: Core and surface temperatures at 60 mm cross-sectional surface diameter, 5 mm and 10 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-13 shows the variation in surface temperatures and core temperatures for the 5 mm and 10 mm thick samples. The core and surface temperatures for the 10 mm samples have an average of 33 °C and 31 °C respectively. The 5 mm samples have averages of 30 °C and 29 °C. The temperatures are similar showing the FS was isothermal through the drying process hence experiencing no heat transfer limitations. As a result, there are no heat and mass transfer limitations.

4.1.4 Effect of surface area

The surface area exposed to solar irradiation is critical to solar based energy methods as this is directly related to the energy input into the system. The effect of the surface area on the solar drying of faecal sludge was explored in Figure 4-14 and Figure 4-15. The investigated surface areas were 0.00283 m^2 (sample of 60 mm diameter) and 0.0113 m^2 (sample of 120 mm diameter) representing an increase in surface area of 400 %.

Figure 4-14: Mass ratio variation as a function of time during the open air sun drying and solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

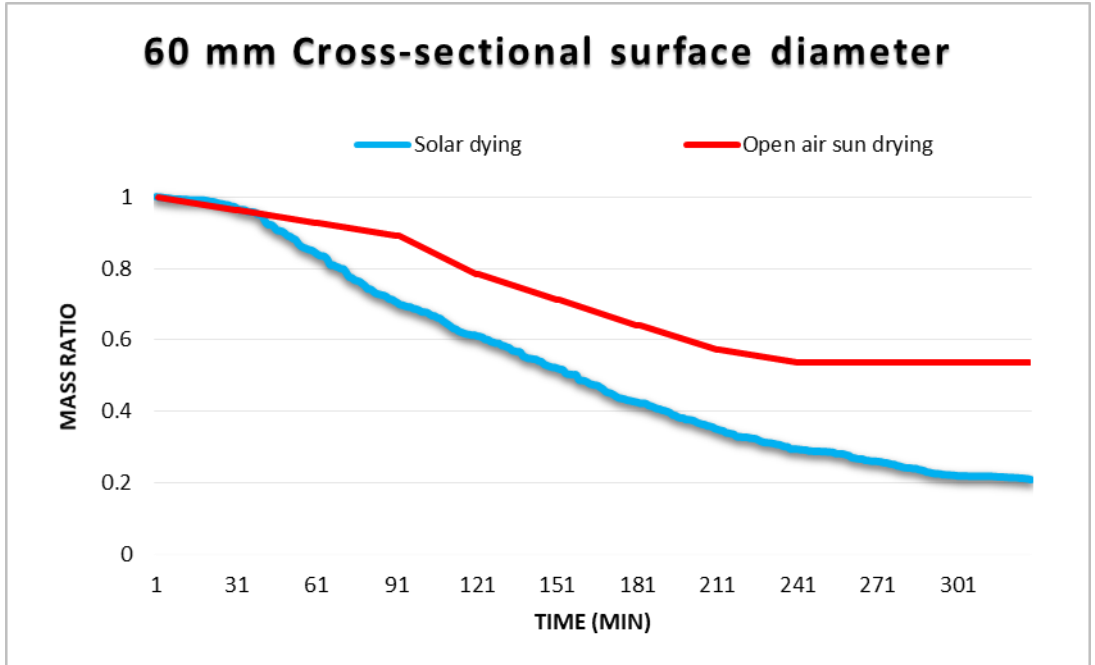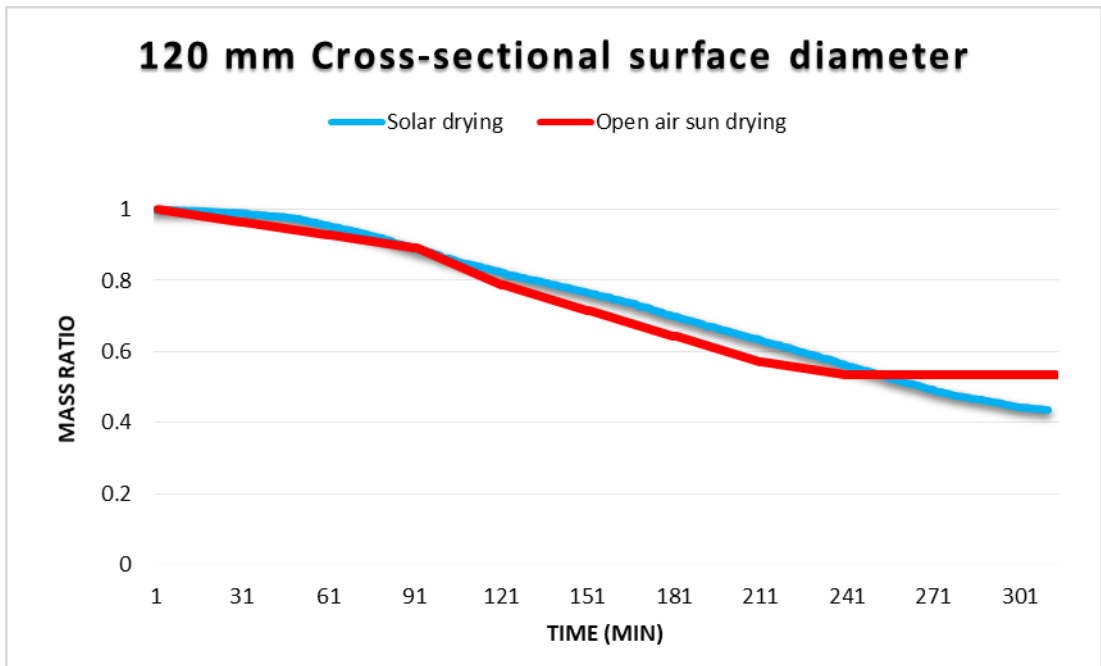**Figure 4-15: Mass ratio variation as a function of time during the open air sun drying solar drying of FS at 120 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions**

Figure 4-14 and Figure 4-15 compare the drying kinetics of the 60 mm and 120 mm solar and sun drying properties. As expected, solar drying presented a better performance with a difference of 0.35 in favour of the solar drying for the 60 mm diameter samples, showing an increased drying rate. The drying kinetics were similar for the 120 mm diameter samples. Based on the obtained results, increasing the surface area slightly reduced the deficit, but still favoured solar drying over sun drying.

Figure 4-16: Mass ratio variation as a function of time during the open air sun drying of FS at 60 mm and 120 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-16 compares the drying curves of the sun-dried samples with different diameters (so different surface area). The final mass ratios were 0.50 and 0.55 for the 60 mm and 120 mm samples, and the average drying rate of 0.686 kg/h.m^2 and 0.607 kg/h.m^2 respectively. This result confirms that the area is directly related to the mass of moisture lost but maintains drying rate being the same per unit surface area.
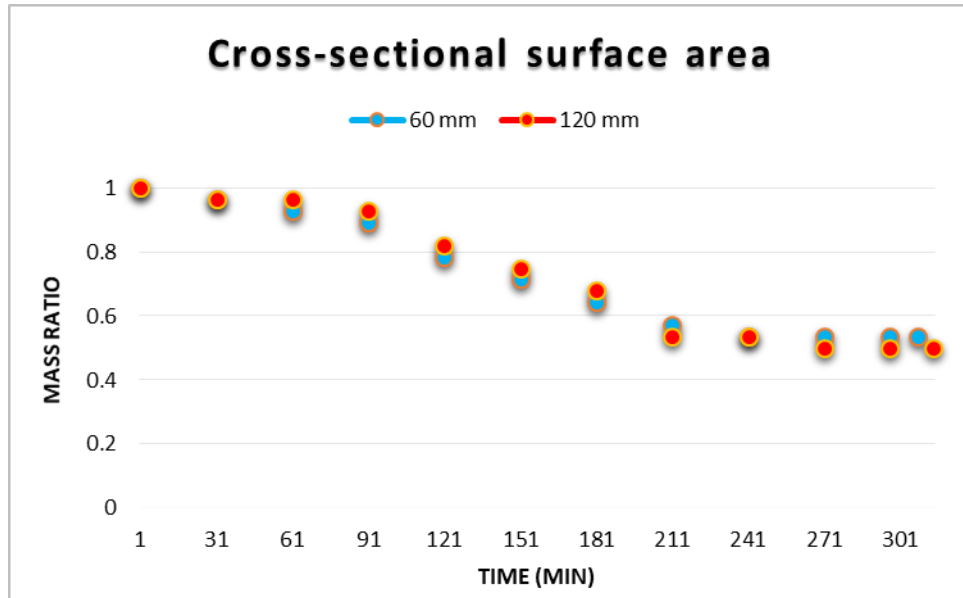
Figure 4-17: Mass ratio variation as a function of time during the solar drying of FS at 60 mm and 120 mm cross-sectional surface diameter, 5 mm and 10 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-17 compares the drying curves of the solar dried samples. The final mass ratios were 0.20 and 0.30 for the 60 mm and 120 mm diameter samples, with respective average drying rates of $1.066 \, kg/h.m^2$ and $0.944 \, kg/h.m^2$. Again, the drying rates are comparable, showing the same drying kinetics per unit of surface area.
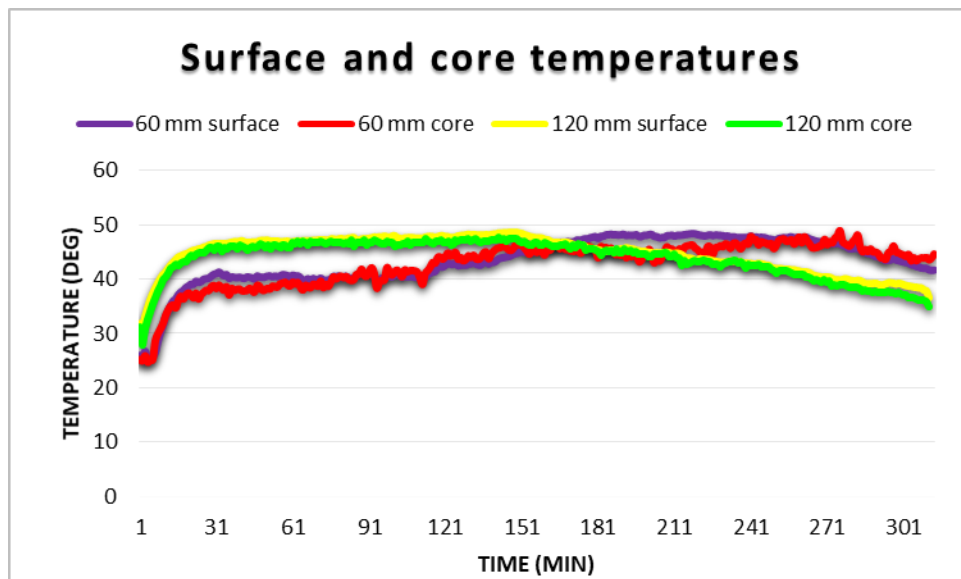
Figure 4-18: Surface area surface and core temperatures at 60 mm and 120 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-18 shows the core and surface temperatures of the 60 mm and 120 mm samples. The core temperatures averaged 40 °C and 43 °C respectively, the surface temperatures averaged 35 °C and 40 °C. This showed no significant variation and little effect of varying the surface area on the temperature profiles.

4.1.5 Effect of the air flowrate

According to Hossain, Woods et al. (2007), the rate of drying is highly influenced by the airflow velocity passing through the system. According to Makununika (2016), low airflow variations did not affect drying kinetics during convective drying, under the explored range (0.03 cm/s to 0.12 cm/s). Hence, there is need to confirm this result with higher airflow velocities such as done in this study. So, the effect of this parameter was investigated on the drying of FS. The investigated cross-sectional flow velocities were 0 (no forced air convection), 0.5 m/s ± 0.1 m/s and 1.0 m/s ± 0.1 m/s.

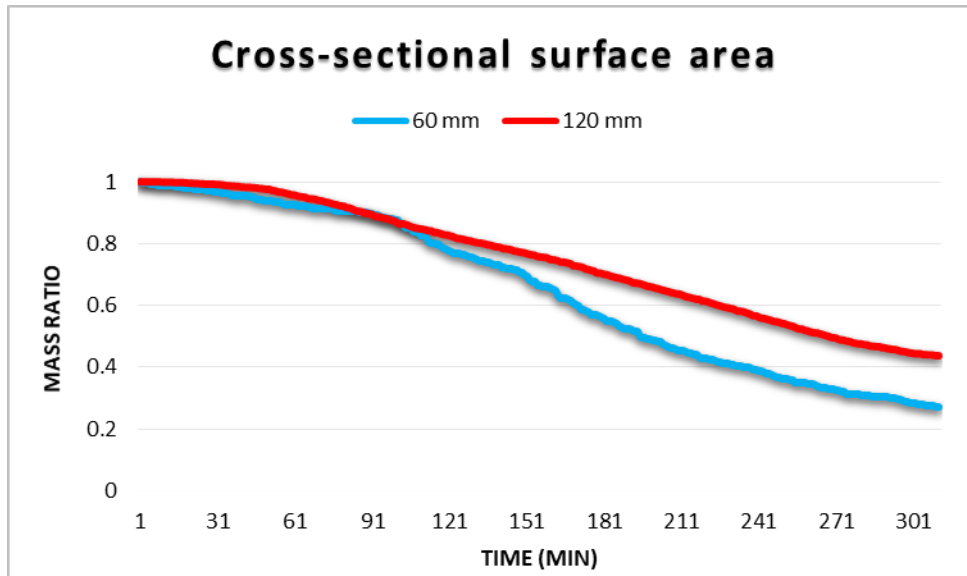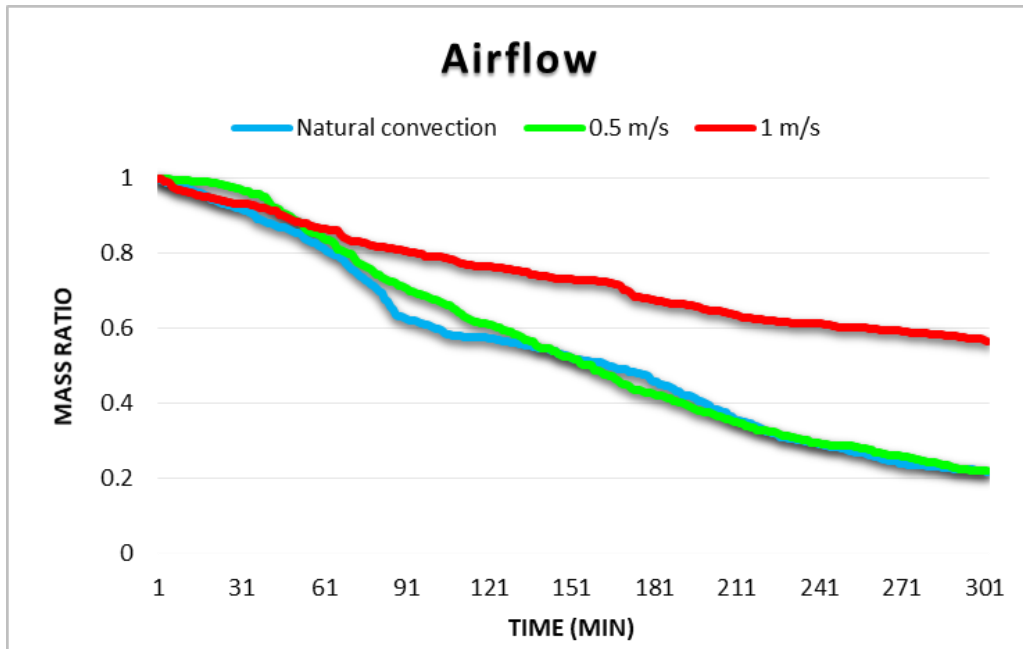**Figure 4-19: Mass ratio variation as a function of time during the solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness, natural convection, 0.5 m/s and 1.0 m/s air flow rate without applying air preheating under sunny conditions**

Figure 4-19 shows the drying kinetics of solar drying exposed to varying airflow velocities. There was no variation between natural convection and 0.5 m/s airflow velocity. In accordance to the findings of Hossain, Woods et al. (2007), there exists a threshold airflow rate above which drying is not enhanced, and in some cases the drying phenomenon can be hindered resulting in a reduced drying rate. This could be attributed to the reduced transfer of moisture time.

The 1 m/s air flow velocity experienced lower drying kinetics compared to no forced air convection and 0.5 m/s airflow velocity. The samples exposed to 1 m/s formed hard crusts and this restricted the drying process by hindering the transfer of moisture to the surface. The samples also experienced cracking which corresponded to step-like drops in the drying curve, aiding the drying process. The natural convection and 0.5 m/s drying kinetics were similar, this was due to natural convection having a low flow velocity, hence aiding the drying rate and making it comparable to 0.5 m/s, and also highlighting the possibility of no considerable effect on the drying rate between 0.0 m/s and 0.5 m/s air flow velocity. It was observed that, the 0.5 m/s samples developed a crust, but though not as hard as 1.0 m/s, hence decreasing the drying rate and making it comparable to natural convection.
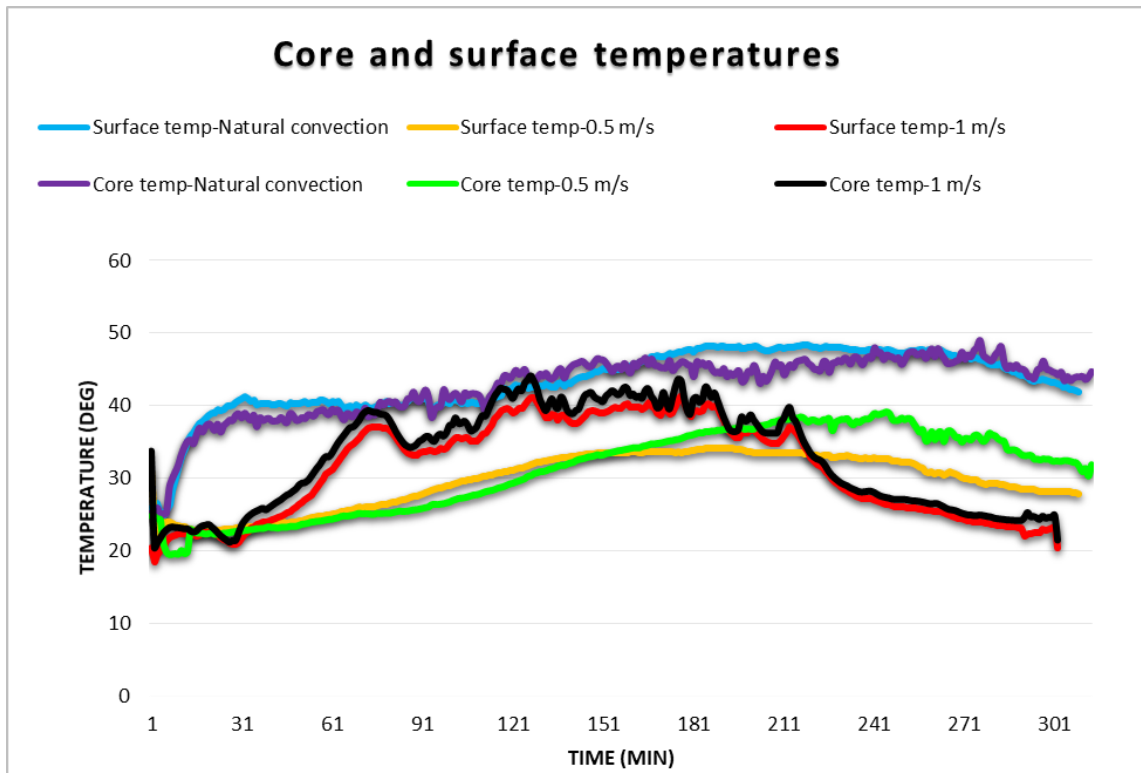

Figure 4-20: Core and surface temperatures at 60 mm cross-sectional surface diameter, 5 mm thickness, natural convection, 0.5 m/s and 1.0 m/s air flow rate without applying air preheating under sunny conditions

Figure 4-20 show the temperature measurements at the different air flowrates. The temperature are similar, which may be due to the fact that the experiments were done in the same weather conditions (sunny), with only the air flowrate differing. Hence, the airflow velocity should not significantly affect the thermal behaviour of the system.

4.1.6 Effect of air preheating

The temperature of air directly affects the moisture reticulation properties of the air, influences the heat and mass transfer rates, increases the energy input to the system for drying and influences the drying capabilities of the air. The effect of air preheating was investigated in order to determine how temperature influences the drying air during solar drying kinetics of FS. The investigated conditions were 'no preheat', meaning no pre-heating of the air, and pre-heating at 30 °C and 60 °C.
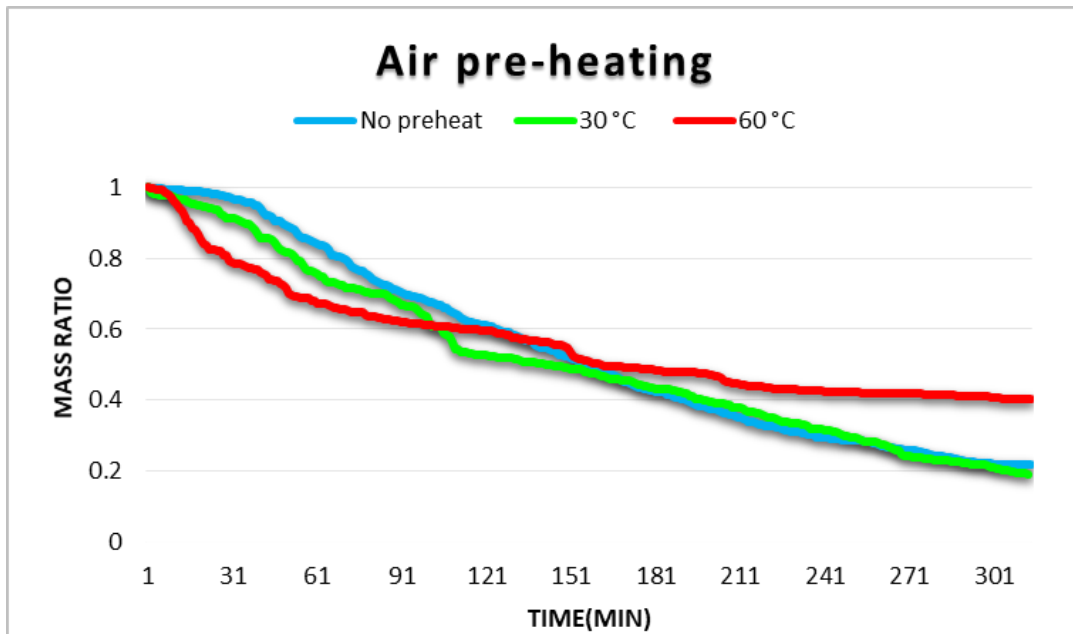

Figure 4-21: Mass ratio variation as a function of time during the solar drying of FS at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate whilst applying no preheat, 30 °C and 60 °C air preheating under sunny conditions

Figure 4-21 shows the drying curves for no preheat, 30 °C and 60 °C preheating. The final achieved mass ratios were 0.20, 0.20 and 0.40 respectively, and the average drying rates 1.066 kg/h.m², 1.135 kg/h.m² and 0.749 kg/h.m² respectively. Unexpectedly, drying with 60 °C preheat performed poorly, only achieving a final mass ratio of 0.40. The 60 °C drying curve presented an initially high drying rate, as defined by a steep curve in the first hour of drying, then dropped significantly to attain a plateau as drying proceeded for the rest of the experiment. This drop could be due to the quick formation of a hard crust on the surface of the FS, as noted after the observation of the sample dried under these conditions.
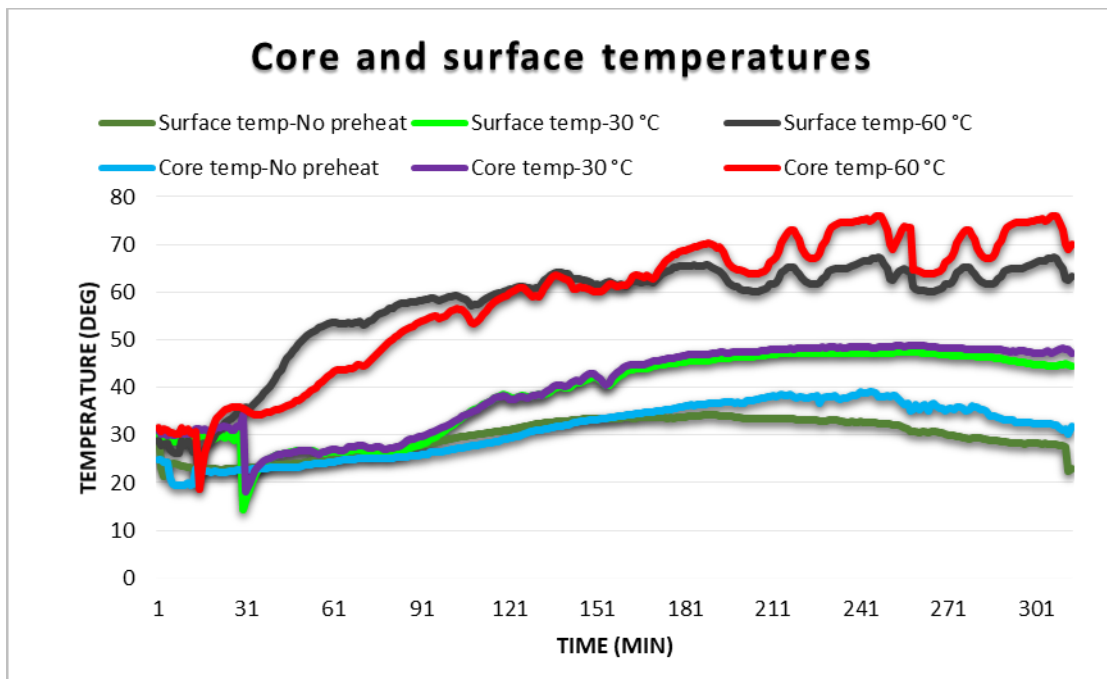

Figure 4-22: Surface and core temperatures at 60 mm cross-sectional surface diameter, 5 mm thickness and 0.5 m/s air flow rate whilst applying no preheat, 30 °C and 60 °C air preheating under sunny conditions

Figure 4-22 shows the core and surface temperatures for no preheat, 30 °C and 60 °C preheat samples. The curves for no preheat and 30 °C preheat showed minimal differences as the drying temperatures recorded were similar, with an average of 31 °C and 37 °C respectively. The surface temperature curves showed a steep increase in the drying temperature before reaching a plateau. The core temperature graphs showed a more gradual and constant increase through the experiment to a temperature slightly above the drying temperatures and followed a similar temperature trend to the surface temperature curve, although no significant difference was noted between the core and surface temperature profiles.

4.2   Analysis of physico-chemical properties of faecal sludge

This section details the analysis carried out on the dried FS to determine the effect of solar drying on the thermal properties and nutrient content. The nutrient content of the FS is important to the resource recovery of FS as a fertiliser and soil conditioner. The thermal properties and calorific value are important for the reuse of FS as a biofuel for combustion and for the design of thermal processes. The physical properties of the FS give an indication of the state of the FS. The overall of the investigated parameters included shrinkage, density, ash content, moisture content, thermal conductivity, gross heat, heat capacity, calorific values, molecular and elemental nutrients. Table 4-1 displays the key reference corresponding to the sample obtained at the different tests.

Table 4-1: Reference of the samples as a function of the conducted test for reference for results in Figure 4-23 to Figure 4-28

SAMPLE KEY REFERENCE	TEST
1	Sunny conditions open air drying
2	Cloudy conditions open air drying
3	Overcast conditions open air drying
4	Natural convection
5	0.5 m/s flow velocity-Sunny-5mm thicknes-60mm diameter-no preheat (base line)
6	1 m/s flow velocity
7	Cloudy
8	Overcast
9	10 mm thickness
10	30 °C preheat
11	60 °C preheat
12	120 mm diameter
13	Wet sample

4.2.1   Moisture content

The moisture content refers to the amount of moisture in a material. It is an indication of the extent of drying that the material undergone.
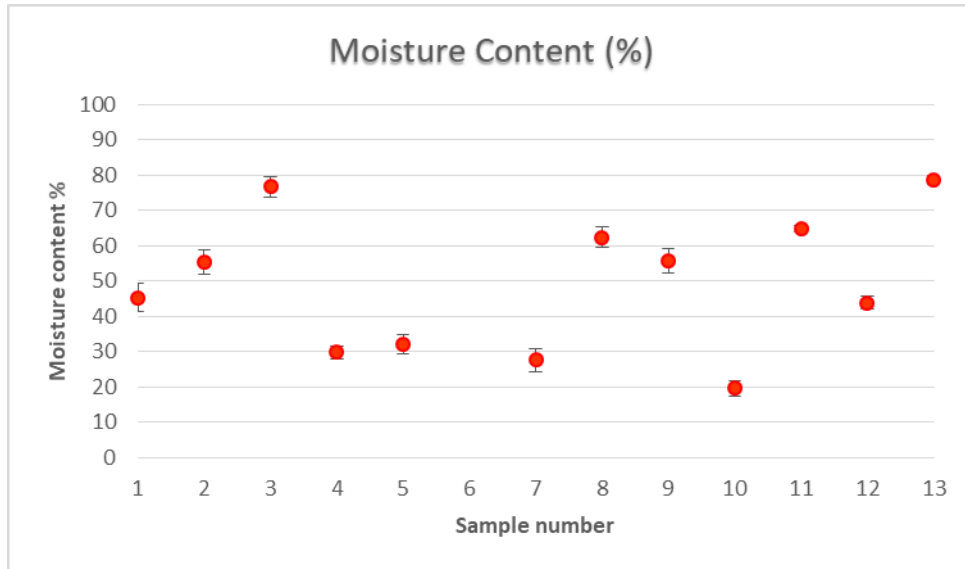
Figure 4-23: Moisture content of FS after solar and open air sun drying under varying drying conditions including the raw FS prior to drying

Figure 4-23 shows the moisture content of the samples. The initial moisture content of the sludge was measured at 78 %, consistent with the findings of Makununika (2016) and Mirara (2017). Indeed, this result is consistent with the typical moisture content of the FS from the VIP latrines in the eThekwini municipality, with the average value recorded at 80 %.

The lowest measured moisture content values were 20 %, 27 %, 29 % and 31 % for samples 10, 7, 4 and 5 respectively. These were directly related to the drying performance of the drying conditions. The samples with lower moisture content also had higher drying rates and achieved higher mass loss during drying.

Sun drying in overcast conditions (sample 3) had the least reduction of moisture content, with a value measured at 77 %. Sun drying recorded moisture content of 45 %, 55 % and 77 % for samples 1, 2 and 3 respectively, showing a trend similar to their respective moisture loss characteristic profiles. Air preheat temperature, sample thickness and cross-sectional surface area variations followed similar trends of moisture content as the drying kinetics.

The moisture content showed a high dependence on the drying performance of the investigated drying conditions. The measurement of the moisture content from sample 6 was considered as an error, as the value deviated from expected range of the final moisture content.

4.2.2   Ash content

The ash content represents the inorganic matter remaining after removal of all the organic elements from the FS. This indicates the final residue remaining after removal of all organic matter from the sludge.
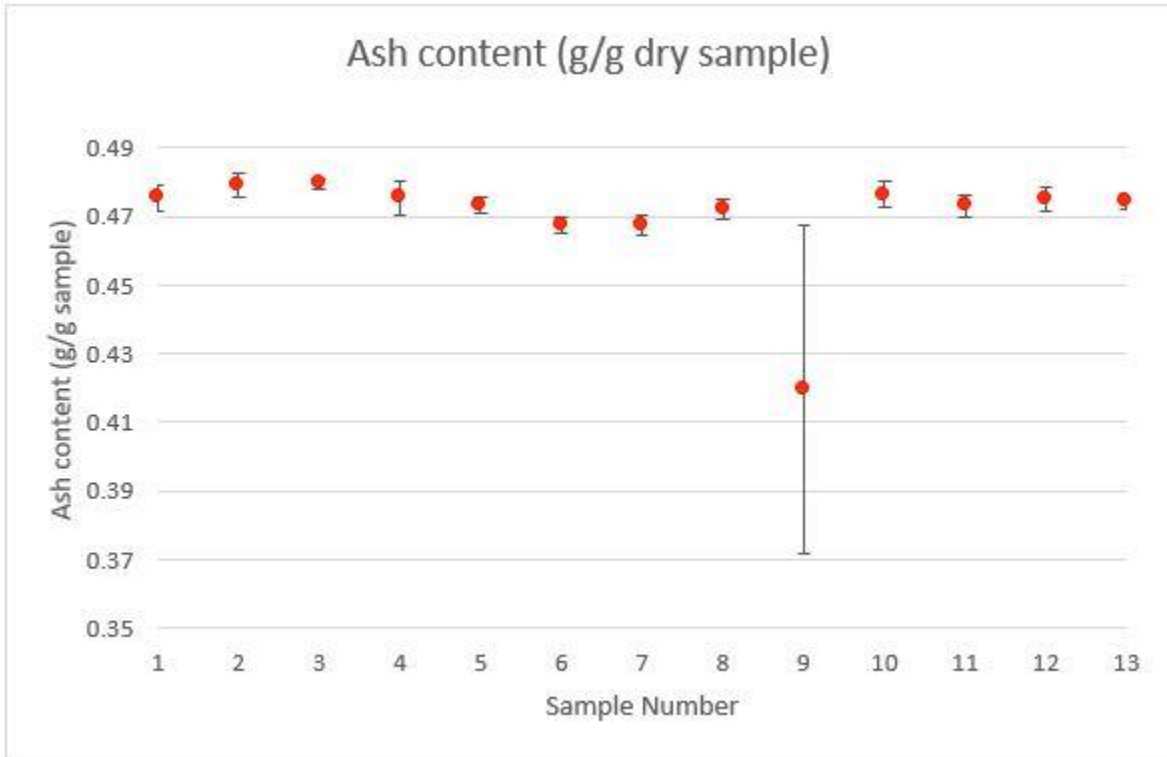

Figure 4-24: Ash content values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying

Figure 4-24 shows the ash content of the samples. There is no notable variation of the ash content under the different explored conditions, demonstrating that there was no thermal degradation of the sludge during solar and open-air sun drying. The average ash content was recorded at 0.468 g/g dry sample, consistent with the findings of Zuma, Velkushanova et al. (2015) who conducted a research to characterize the FS from VIP latrines in the eThekwini municipality.

4.2.3   Shrinkage

Shrinkage refers to the final volume of the sample in comparison to the initial volume. It indicates the reduction of volume of FS after drying. The volume of FS influences the operational costs of transportation to the post-treatment plant or the location of reuse of the dried product.
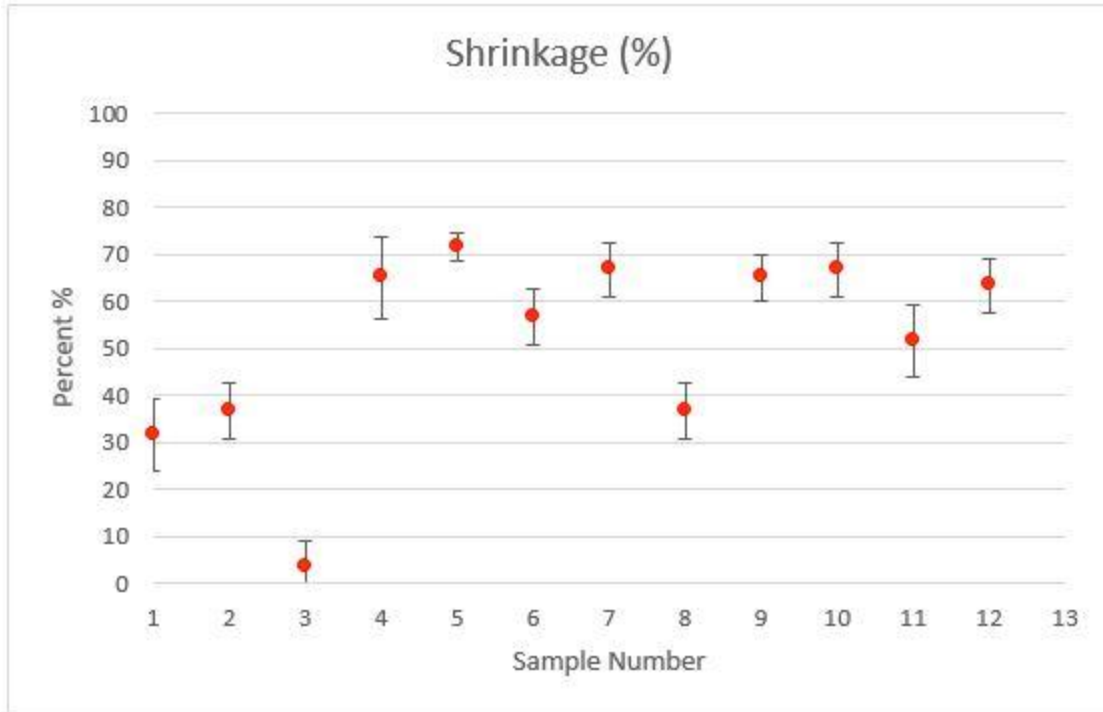
Figure 4-25: Shrinkage values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying

Figure 4-25 shows the shrinkage of faecal sludge after solar drying. The results show that the shrinkage is directly related to the mass of the moisture lost. The highest achieved shrinkage values were 70 % for samples 5, 7 and 10, and 65 % for sample 9. The lowest achieved shrinkage values were 0 %, 30 %, 40 % and 40 % corresponding to samples 3, 1, 2 and 8 respectively.

Sun drying had lower shrinkage values compared to solar drying. Indeed, solar drying led to higher shrinkage compared to sun drying, 0 % versus 40 % for overcast conditions (samples 3 and 8 respectively), 30 % versus 70 % for sunny conditions (samples 1 and 5 respectively) and 40 % versus 70 % for cloudy conditions (samples 2 and 7 respectively). It can be noted that shrinkage in solar drying in overcast conditions (sample 8) is comparable to the best achieved open-air sun drying shrinkage values.

Weather conditions had a great effect on the shrinkage values, with an increase from 0 % to 40 % and 40 % to 70 % from overcast to sunny condition, for sun drying (samples 3 and 2 respectively) and solar drying respectively (samples 8 and 5 respectively). Air preheating temperature showed similar shrinkage of 70 % for sample 5 to sample 10, and a decrease from 70 % to 50 % from sample 10 to sample 11. This was attributed to the increase of the drying performance of sample 5 compared to sample 10 and decrease in drying performance for sample 10 in comparison to sample 11.

Flow velocity had a slight variation in shrinkage, from 60 % for both sample 4 and sample 6, with sample 5 presenting 70% of shrinkage. Surface area and sample thickness did not significantly affect shrinkage, recording final values of 70 % and 65 % for sample 12 and sample 9 respectively, this was due to these properties experiencing similar drying performance.

The shrinkage was noted to depend on the moisture content of the sample. The relationship was noted to be inversely proportional with the decrease of moisture leading to a higher shrinkage.

4.2.4 Density

Density is a measure of the relationship between the mass of a material and the volume that it occupies. Volume and mass characteristics are critical for transport logistics. Change in the density characteristics varies the mass per unit volume of FS.
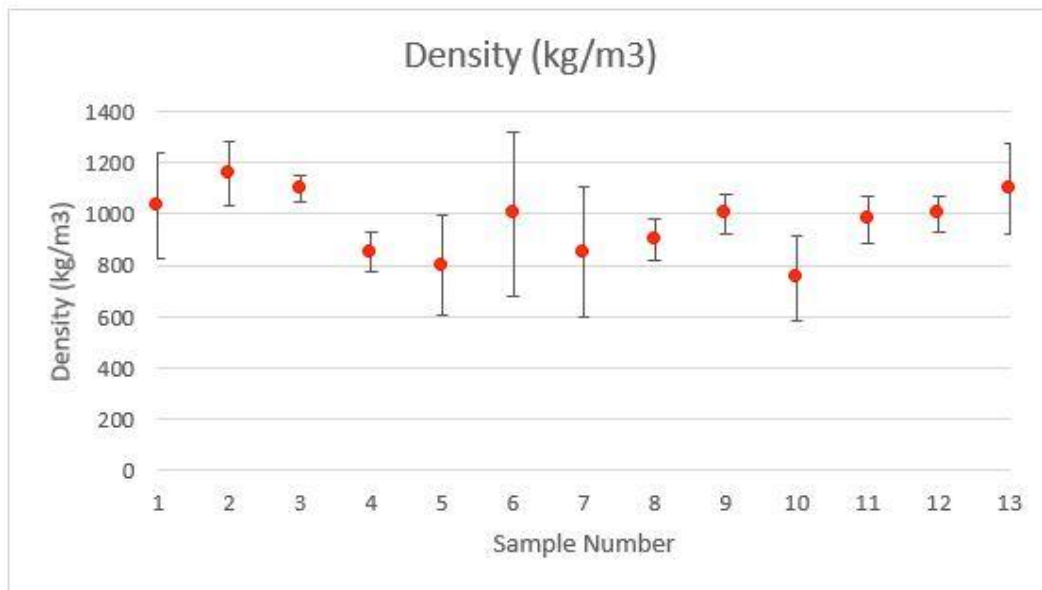

Figure 4-26: Density values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying

Figure 4-26 shows the density values of the samples. There was minimal variation of density between sample 13, the open air sun dried samples (samples 1, 2 and 3), sample 11 and sample 8, having a spread of density values ranging from 1 000 kg/m^3 and 1 160 kg/m^3, with the density of the wet sludge measured at 1 100 kg/m^3. There was a considerable difference with respect to sample 10 with a final density of 600 kg/m^3. Air preheating affected the density significantly, recording values of 750 kg/m^3, 800 kg/m^3 and 1 000 kg/m^3 for samples 10, 5 and 11 respectively.

The airflow rate did not have a significant influence on the density, ranging from 800 kg/m^3 to 1000 kg/m^3 for samples 4, 5 and 6. Sample thickness and cross-sectional surface area (samples 9 and 12) increased the density, exhibiting values of 1000 kg/m^3, whereas the density of sample 5 was of 850 kg/m^3.

The density showed dependence on shrinkage and the moisture content. The lower the recorded shrinkage and higher moisture content resulted in a higher density, close to the density of the wet FS sample. A linear relationship was noted with moisture content as the density depended on the amount of moisture in the sample

4.2.5 Thermal conductivity

Thermal conductivity refers to the ability of a material to conduct heat. Thermal conductivity is a critical property for thermal process, such as drying and combustion.
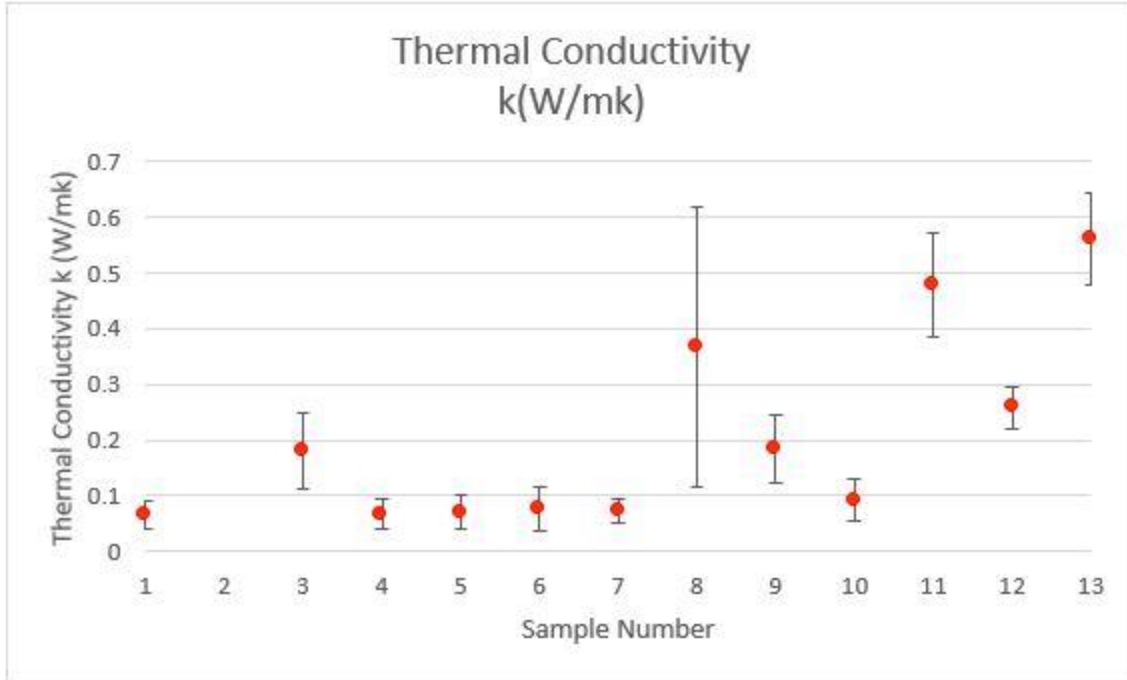
Figure 4-27: Thermal conductivity values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying

Figure 4-27 shows the thermal conductivity of the samples. The thermal conductivity of the wet sludge was measured at 0.56 W/m.K, similar to the thermal conductivity of water (0.6 W/m.K). This may be due to the high moisture content of the FS, which controls its thermal conductivity.

Samples 12, 11 and 8 recorded high thermal conductivity values of between 0.258 W/m.K and 0.478 W/m.K, whereas samples 4, 5, 6, 7 recorded low thermal conductivity values averaging 0.0719 W/m.K. A similar trend was noted between the samples for moisture content. Hence, thermal conductivity was observed to decrease with the reduction of moisture content during the drying of the sample.

4.2.6 Heat capacity

The heat capacity of a material refers to the energy required, added or removed, to lead to the variation of its temperature. The ability to predict the heat capacity of a material is critical for the design of thermal processes.
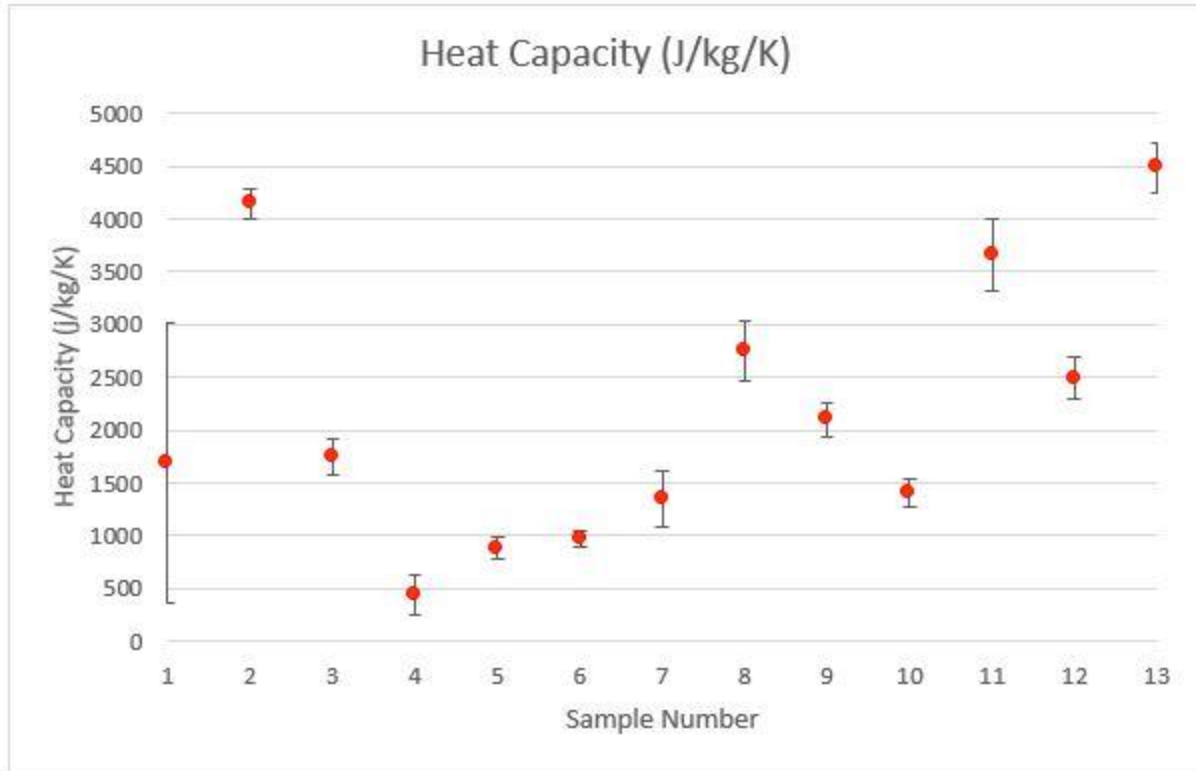
Figure 4-28: Heat capacity values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying

Figure 4-28 shows the heat capacity of the different samples. The heat capacity of the wet sludge was 4.476 kJ/kg.K, a value close to the heat capacity of water ($\approx$ 4.2 kJ/kg.K). These values were comparable due to the high moisture content of the FS. The heat capacity values of the dried FS ranged from 0.360 kJ/kg.K to 3.66 kJ/kg.K.

Samples 2, 8, 11 and 12 shown high heat capacity values, ranging between 2 486 J/kg.K and 4 142 J/kg.K, whereas samples 4, 5, 6, 7 presented low heat capacity values averaging 910 J/kg.K. Similar to thermal conductivity, the moisture content greatly affected the heat capacity, as the reduction of moisture content led to a lower heat capacity.

4.2.7 Calorific values and Nutrient analysis

Calorific values gives an indication of the energy released by a substance, for instance, during combustion. FS can potentially be reused as a biofuel for heating and energy production purposes.

As FS is biological matter it contains various nutrients which make it applicable as a fertiliser and/or soil conditioner. As a result, it is critical to analyse the nutrient concentration of the sludge to determine the value to agriculture of dried FS. The analysed nutrients were orthophosphates, nitrates, ammonium, carbon, nitrogen and sulphur.

The results for the calorific values and nutrient analysis lacked reliability due to conflicting findings. These are available in Appendix E.

4.3   Qualitative analysis

Quantitative analysis of the solar drying of FS was carried out. This included the detection of the formation of cracks and crust, as well as colour and odour variation after drying. The formation of cracks and crust is essential for the drying of FS as it directly affects the drying rates. The odour is critical for the social acceptance of FS reuse.

Table 4-2: Quantitative analysis of colour variation, crust, cracks and odour of the open air sun dried and solar dried FS samples

SAMPLE NUMBER	TEST	COLOUR VARIATION	CRUST	CRACKS	ODOUR
1	Sunny control	No change	Yes - thin	No	Slightly stronger
2	Cloudy control	No change	Yes - thin	No	No change
3	Overcast control	No change	No	No	No change
4	Natural convection	No change	Yes - thin	No	Slightly stronger
5	0.5 m/s flow velocity-Sunny-5 mm thicknes-60 mm diameter-no preheat	Slightly darker brown	Yes	Yes - slight	Slightly stronger
6	1m/s flow velocity	Slightly darker brown	Yes	Yes	Slightly stronger
7	Cloudy	No change	Yes - thin	Yes - slight	No change
8	Overcast	No change	No	No	No change
9	10 mm thickness	No change	Yes	Yes-slight	Slightly stronger
10	30 °C preheat	Darker brown	Yes - thick	Yes	Stronger
11	60 °C preheat	Darker brown	Yes - very thick	Yes - slight	Stronger
12	120 mm diameter	No change	yes	Yes - slight	Slightly stronger

Table 4-2 shows the colour variation, odour, crack and crust formation characteristics of the various samples. The base of the comparison was with respect to the wet FS.

There was a slight change in colour for the samples exposed to 0.5 m/s (sample 5) and 1 m/s (sample 6), while a significant change was noticed for 30 °C air preheating (sample 10) and 60 °C air preheating (sample 11). The colour varied to a darker shade of brown in comparison to the wet FS. This showed that the drying temperature affected the colour variation significantly as these samples were exposed to higher temperatures.

Crust formation was experienced in most of the conditions, with the exception of overcast conditions in both solar and sun drying. Air preheating exposed the samples to harder crusts. Increasing the airflow velocity also caused important crusting as seen for the 1 m/s sample (sample 6).

Crack formation was experienced more often as the airflow velocity varied. Less crack formation was noticed for 60 °C air preheating (11) as this caused a rapid formation of a hard crus, as crack formation becomes more difficult.

The moisture content was found to greatly affect the odour strength of the samples – the lower the moisture content, the stronger the odour. The drying temperature also played a role as the 30 °C air preheating (10) and 60 °C air preheating (11) samples experienced a stronger odour although the latter had a higher moisture content.

CHAPTER 5: CONCLUSIONS

Solar and open air sun drying of FS from VIP latrines were investigated at different experimental conditions. Weather conditions showed significant influence on the drying rate for both solar drying and open air sun drying.

For open air sun drying the weather conditions were found to be critical to the drying performance with the lowest mass ratios of 0.530. Drying performance was poor in overcast drying conditions, recording a final mass ratio of 0.963. Sample thickness and surface area in the investigated ranges did not exhibit any influence on the drying performance.

Weather conditions, air flow velocity, air preheating, crusting and cracking exhibited a profound impact on the solar drying performance. Under solar drying, final mass ratio values of 0.219, 0.296 and 0.582 for sunny, cloudy and overcast conditions respectively; 0.297, 0.219 and 0.567 for natural convection, 0.5 m/s air flow velocity and 1 m/s air flow velocity respectively; and 0.219, 0.193 and 0.402 for no air preheating, 30 °C air preheating and 60 °C conditions respectively. Crusting and cracking were found to be responsible for the poor performance under 1 m/s air flow velocity and 60 °C air preheat temperature drying conditions. Sample thickness and surface area in the investigated ranges did not exhibit any significant influence on the drying performance.

Open air sun drying showed the capacity to dry FS, but solar drying showed better drying capacity and hence shortening drying times by at least 50 % compared to open air sun drying. Solar drying also demonstrated drying potential in all weather conditions, including overcast conditions. Solar drying presented higher drying rates, averaging 0.892 $kg/h.m^2$ across all the investigated parameters, compared to 0.479 $kg/h.m^2$ for open air sun drying.

Temperature profiles were characterised through the experiments. The greenhouse effect increased drying chamber temperatures above ambient temperatures. The airflow velocity was also noted to have an impact on the chamber temperature, as this resulted in a cooling effect. The cooling effect was noted to be averted by air preheating. Core and surface temperatures followed similar temperature trends to each other. Weather conditions were noted to greatly affect temperature profiles. Average drying chamber temperatures were 32 °C, 29 °C and 21 °C for sunny, cloudy and overcast conditions with ambient temperatures recording 26 °C, 25 °C and 19 °C respectively.

The moisture content of the wet sludge was measured at 78 %, similar to past research. The final moisture content was dependent on the drying parameters, recording an average final moisture content of 26 % for 30 °C air preheating, sunny conditions solar drying and natural convection air flow characteristics. The shrinkage, thermal conductivity, heat capacity, odour intensity and colour characteristics closely followed the moisture content. Final recorded shrinkage average values of 67 % for 30 °C air preheating, sunny conditions solar drying and natural convection air flow characteristics. The thermal conductivity of the raw FS was 0.561 W/m.K. The average thermal conductivity of the dried samples was 0.119 W/m.K. The heat capacity of the wet sludge was measured at 4.476 kJ/kg.K. This value decreased with loss of moisture to a low of 0.436 kJ/kg.K. The odour intensity of the sludge was stronger as the material was more dried. The colour varied slightly with drying, as the dried samples had a darker brown colour than the wet samples. The density was dependent on the moisture content and shrinkage properties.

The ash content remained uniform through the experiments, showing that no thermal degradation of the sludge was experienced in both solar drying and open air sun drying. Overcast open air sun drying characteristics showed no variation with shrinkage, density and moisture content. The average calorific value of the wet sludge was recorded at 13 MJ/kg and for the dried sludge at 6.364 MJ/kg. Air flow velocity and preheating were critical in the formation of cracks and crust and were found to be the critical contributors to the hardness of the crust and the quantity of cracks.

CHAPTER 6: RECOMMENDATIONS

The prototype was built at a laboratory scale to mimic the process of drying in a solar thermal system (such as greenhouse dryer). Recommend to build a large scale solar dryer.

The tests were conducted during spring, Recommend to test the equipment in other seasons.

Ascaris deactivation was not investigated due to lack of viable eggs in the sample. Recommend to perform this analysis in the future, with eventual spiking of viable eggs if not present in the sludge.

I would recommend the use of a mathematical model of the solar system, such as Comsol, in order to aid in the comparison as well as proposal of design modifications.

REFERENCES

Adair, D. (1985). *Improved sundrying and solar drying: basic considerations and selected applications*: Food and Agriculture Organization of the United Nations.

Akoy, E., Ismail, M. A., Ahmed, E.-F. A., & Luecke, W. (2006). *Design and construction of a solar dryer for mango slices*. Proceedings of International Research on Food Security, Natural Resource Management and Rural Development,Tropentag. University of Bonn, Bonn, Germany.

Alahmer, A., Omar, M., Mayyas, A., & Dongri, S. (2011). Effect of relative humidity and temperature control on in-cabin thermal comfort state: Thermodynamic and psychometric analyses. *Applied Thermal Engineering, 31*(14-15), 2636-2644.

Almeida, M., Butler, D., & Friedler, E. (1999). At-source domestic wastewater quality. *Urban Water, 1*(1), 49-55.

Alsharkawi, A., & Rossiter, J. A. (2016). Dual mode mpc for a concentrated solar thermal power plant. *IFAC-PapersOnLine, 49*(7), 260-265.

Annamraju, S., Calaguas, B., & Gutierrez, E. (2001). *Financing water and sanitation. Key issues in increasing resources to the Sector*. Water Aid briefing paper. London: Water Aid.

Archuleta, R., Berkey, J., & Williams, B. (1983). Research on solar food drying at the University of California, Santa Cruz. Progress in passive solar-energy systems. *Amer Solar Energy Soc Inc*, 679-683.

Arinze, E. A., Schoenau, G., & Bigsby, F. W. (1979). *Solar-energy absorption properties of some agricultural products*. ASAE paper No. 79–3071, American Society of Agricultural Engineers, St. Joseph, MI, USA.

Arlabosse, P., Chavez, S., & Lecomte, D. (2004). Method for thermal design of paddle dryers: Application to municipal sewage sludge. *Drying Technology, 22*(10), 2375-2393.

Austin, L., & Van Vuuren, S. (2001). Sanitation, public health and the environment: looking beyond current technologies. *Journal of the South African Institution of Civil Engineering= Joernaal van die Suid-Afrikaanse Instituut van Siviele Ingenieurswese, 43*(1), 29-33.

Bacelos, M. S., & Almeida, P. I. F. (2011). Modelling of drying kinetic of potatoes taking into account shrinkage. *Procedia Food Science, 1*(0), 713-721.

Bahnasawy, A. H., & Shenana, M. (2004). A mathematical model of direct sun and solar drying of some fermented dairy products (Kishk). *Journal of Food Engineering, 61*(3), 309-319.

Bakare, B., Foxon, K., Brouckaert, C., & Buckley, C. (2012). Variation in VIP latrine sludge contents. *Water SA, 38*(4), 479-486.

Balint, P. J. (1999). Drinking water and sanitation in the developing world: the Miskito Coast of Nicaragua and Honduras as a case study. *Journal of Public and International Affairs, 10*(1), 99-117.

Banerjee, R. (2005). *Capacity building for renewable energy in India.* Paper presented at the Proceedings of International congress on Renewable Energy (ICORE 2005), January, Pune India.

Banga, J. R., & Singh, R. P. (1994). Optimization of air drying of foods. *Journal of Food Engineering, 23*(2), 189-211.

Basunia, M., & Abe, T. (2001). Thin-layer solar drying characteristics of rough rice under natural convection. *Journal of Food Engineering, 47*(4), 295-301.

Bergman, T. L., Incropera, F. P., Lavine, A. S., & DeWitt, D. P. (2011). *Fundamentals of heat and mass transfer*. New York: John Wiley & Sons.

Boesch, M. E., & Hellweg, S. (2010). Identifying improvement potentials in cement production with life cycle assessment. *Environmental Science & Technology, 44*(23), 9143-9149.

Bolaji, B. O., & Olalusi, A. P. (2008). Performance evaluation of a mixed-mode solar dryer. *AU Journal of Technology, 11*(4), 225-231.

Bolaji, B. O., Olayanju, T. M., & Falade, T. O. (2011). Performance evaluation of a solar wind-ventilated cabinet dryer. *The West Indian Journal of Engineering, 33*(1/2), 12-18

Bosshard, P., Hermann, W., Hung, E., Hunt, R., & Simon, A. (2006). *An assessment of solar energy conversion technologies and research opportunities*. GCEP Energy Assessment Analysis, Standford University, California, USA.Summer 2006.

Box, F. (2010). Improving sanitation in Ghana-role of sanitary biogas plants. *Journal of Engineering and Applied Sciences, 5*(2), 125-133.

Brouckaert, C., Foxon, K., & Wood, K. (2013). Modelling the filling rate of pit latrines. *Water SA, 39*(4), 555-564..

Buckley, C., Foxon, K., Brouckaert, C., Rodda, N., Nwaneri, C., Balboni, E., Magagna, D. (2008a). Scientific support for the design and operation of ventilated improved pit latrines (VIPs) and the efficacy of pit latrine additives. Report to the Water Research Commission, South Africa. Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal.

Calvert, C., Martin, R., & Morgan, N. (1969). House fly pupae as food for poultry. *Journal of Economic Entomology, 62*(4), 938-939.

Chaanaoui, M., Vaudreuil, S., & Bounahmidi, T. (2016). Benchmark of concentrating solar power plants: historical, current and future technical and economic development. *Procedia Computer Science, 83*, 782-789.

Chapuis-Lardy, L., Fiorini, J., Toth, J., & Dou, Z. (2004). Phosphorus concentration and solubility in dairy feces: Variability and affecting factors. *Journal of Dairy Science, 87*(12), 4334-4341.

Čičková, H., Newton, G. L., Lacy, R. C., & Kozánek, M. (2015). The use of fly larvae for organic waste treatment. *Waste Management, 35*, 68-80.

Cofie, O. O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., & Kone, D. (2006). Solid-liquid separation of FS using drying beds in Ghana: implications for nutrient recycling in urban agriculture. *Water Research, 40*(1), 75-82.

Condorí, M., Duran, G., Echazú, R., & Altobelli, F. (2017). Semi-industrial drying of vegetables using an array of large solar air collectors. *Energy for Sustainable Development, 37*, 1-9.

Corcoran, E. (2010). *Sick water? The central role of wastewater management in sustainable development: a rapid response assessment*. United Nations Environment Programme, UN-HABITAT, Nairobi, Kenya.

Coulson, J. (1999). *Coulson and Richardson's chemical engineering Volume 1 – Fluid flow. Heat Transfer and Mass Transfer*. Oxford: Butterworth Heinemann, 1999.

Dail, H. W., He, Z., Susan Erich, M., & Wayne Honeycutt, C. (2007). Effect of drying on phosphorus distribution in poultry manure. *Communications in Soil Science and Plant Analysis, 38*(13-14), 1879-1895.

Department of Water Affairs, (2012). *Report on the status of sanitation services in South Africa.* Pretoria: Government Printer.

Deshmukh, A. W., Varma, M. N., Yoo, C. K., & Wasewar, K. L. (2014). Investigation of solar drying of ginger (zingiber officinale): empirical modelling, drying characteristics, and quality study. *Chinese Journal of Engineering.* http://dx.doi.org/10.1155/2014/305823

Diamante, L. M., & Munro, P. A. (1993). Mathematical modelling of the thin layer solar drying of sweet potato slices. *Solar Energy, 51*(4), 271-276.

Diener, S., Semiyaga, S., Niwagaba, C. B., Muspratt, A. M., Gning, J. B., Mbéguéré, M., Strande, L. (2014). A value proposition: resource recovery from FS—Can it be the driver for improved sanitation? *Resources, Conservation and Recycling, 88*, 32-38.

Doymaz, I. (2007). Air-drying characteristics of tomatoes. *Journal of Food Engineering, 78*(4), 1291-1297.

Doymaz, I., Gorel, O., & Akgun, N. (2004). Drying characteristics of the solid by-product of olive oil extraction. *Biosystems Engineering, 88*(2), 213-219.

Ekechukwu, O. V., & Norton, B. (1999). Review of solar-energy drying systems II: an overview of solar drying technology. *Energy Conversion and Management, 40*(6), 615-655.

El-Sebaii, A., Aboul-Enein, S., Ramadan, M., & El-Gohary, H. (2002). Experimental investigation of an indirect type natural convection solar dryer. *Energy Conversion and Management, 43*(16), 2251-2266.

Fluri, T. P. (2009). The potential of concentrating solar power in South Africa. *Energy Policy, 37*(12), 5075-5080.

Forson, F., Nazha, M., Akuffo, F., & Rajakaruna, H. (2007). Design of mixed-mode natural convection solar crop dryers: application of principles and rules of thumb. *Renewable Energy, 32*(14), 2306-2319.

Franceys, R., Pickford, J., Reed, R., & Organization, W. H. (1992). *A guide to the development of on-site sanitation*: World Health Organization.

Freeman, M. C., Ogden, S., Jacobson, J., Abbott, D., Addiss, D. G., Amnie, A. G., Colford Jr, J. M. (2013). Integration of water, sanitation, and hygiene for the prevention and control of neglected tropical diseases: a rationale for inter-sectoral collaboration. *PLoS Neglected Tropical Diseases, 7*(9), e2439.

Fudholi, A., Sopian, K., Ruslan, M. H., Alghoul, M., & Sulaiman, M. (2010). Review of solar dryers for agricultural and marine products. *Renewable and Sustainable Energy Reviews, 14*(1), 1-30.

Fytili, D., & Zabaniotou, A. (2008). Utilization of sewage sludge in EU application of old and new methods—a review. *Renewable and Sustainable Energy Reviews, 12*(1), 116-140.

Gantzer, C., Henny, J., & Schwartzbrod, L. (2002). Bacteroides fragilis and Escherichia coli bacteriophages in human faeces. *International Journal of Hygiene and Environmental Health, 205*(4), 325-328.

Ghaffari, A., & Mehdipour, R. (2015). Modeling and improving the performance of cabinet solar dryer using computational fluid dynamics. *International Journal of Food Engineering, 11*(2), 157-172.

Gidner, A. V., Stenmark, L. B., & Carlsson, K. M. (2001). *Treatment of different wastes by supercritical water oxidation.* Paper presented at the 20th IT3 Conference. In: Twentieth IT3 Conference, Philadelphia, USA.

Gold, M., Niang, S., Niwagaba, C., Eder, G., Muspratt, A. M., Diop, P., & Strande, L. (2014). *Results from FaME (Faecal Management Enterprises)–can dried FS fuel the sanitation service chain.* Paper presented at the 37th WEDC International Conference.

Goldemberg, J. (2000). *World energy assessment: energy and the challenge of sustainability*. Geneva: United Nations.

Harrison, J., & Wilson, D. (2012). Towards sustainable pit latrine management through LaDePa. *Sustainainable Sanitation Practice, 13*, 25-32.

Hem, S., Toure, S., Sagbla, C., & Legendre, M. (2008). Bioconversion of palm kernel meal for aquaculture: experiences from the forest region (Republic of Guinea). *African Journal of Biotechnology, 7*(8), 1192-1198.

Henley, E., Seader, J., & Roper, D. (2011). *Separation process principles*. New York: John Wiley & Sons.

Hossain, M., & Bala, B. (2002). Thin-layer drying characteristics for green chilli. *Drying Technology, 20*(2), 489-505.

Hossain, M. A., Woods, J. L., & Bala, B. K. (2007). Single-layer drying characteristics and colour kinetics of red chilli. *International Journal of Food Science & Technology, 42*(11), 1367-1375.

Icerman, L., & Morgan, R. P. (1984). Renewable energy technologies for international development, *Energy, 9*(7), 545-554.

Jain, D., & Tewari, P. (2015). Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. *Renewable Energy, 80*, 244-250.

Jayaraman, K., Das Gupta, D., & Babu Rao, N. (2000). Solar drying of vegetables. *Developments in Drying, 1*, 179-206.

Joceline, S. B., Koné, M., Yacouba, O., & Arsène, Y. H. (2016). Planted sludge drying beds in treatment of FS from ouagadougou: case of two local plant species. *Journal of Water Resource and Protection, 8*(07), 697.

Kalogirou, S. A. (2013). *Solar energy engineering: processes and systems*. Cambridge, MA: Academic Press.

Kamwere, M. M. (2017). *Characterising thin layer drying of high moisture content vegetables in a solar tunnel dryer.* MSc. dissertation, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya.

Kant, K., Shukla, A., Sharma, A., Kumar, A., & Jain, A. (2016). Thermal energy storage based solar drying systems: a review. *Innovative Food Science & Emerging Technologies, 34*, 86-99.

Kemp, I. C., Fyhr, B. C., Laurent, S., Roques, M. A., Groenewold, C. E., Tsotsas, E., Kind, M. (2001). Methods for processing experimental drying kinetics data. *Drying Technology, 19*(1), 15-34.

Kiranoudis, C., Maroulis, Z., & Marinos-Kouris, D. (1992). Drying kinetics of onion and green pepper. *Drying Technology, 10*(4), 995-1011.

Komakech, A. J., Banadda, N. E., Kinobe, J. R., Kasisira, L., Sundberg, C., Gebresenbet, G., & Vinnerås, B. (2014). Characterization of municipal waste in Kampala, Uganda. *Journal of the Air & Waste Management Association, 64*(3), 340-348.

Kumar, D. P., Hebbar, H. U., & Ramesh, M. (2006). Suitability of thin layer models for infrared–hot air-drying of onion slices. *LWT-Food Science and Technology, 39*(6), 700-705.

Langergraber, G., & Muellegger, E. (2005). Ecological sanitation—a way to solve global sanitation problems? *Environment International, 31*(3), 433-444.

Léonard, A., Vandevenne, P., Salmon, T., Marchot, P., & Crine, M. (2004). Wastewater sludge convective drying: influence of sludge origin. *Environmental Technology, 25*(9), 1051-1057.

Lopez Zavala, M. A. , et al. (2002). Characterization of feces for describing the aerobic biodegradation of feces. *Doboku Gakkai Ronbunshu* (Journal of Environmental Systems and Engineering) 2002(720): 99-105.

Makununika, B. (2016). *Thermal drying of FS from vip latrines and characterisation of dried faecal material.* Master of Science in Chemical Engineering, University of KwaZulu-Natal, Durban.

Malkki, S. (1999). Human faeces as a resource in agriculture. *Nord. Jordbrugsforskning.*

Maycock, P. D. (2005). PV review: world Solar PV market continues explosive growth. *Refocus, 6*(5), 18-22.

McLean, K. A. (1980). *Drying and storing combinable crops*: Farming Press Ltd.

Mihelcic, J. R., Fry, L. M., & Shaw, R. (2011). Global potential of phosphorus recovery from human urine and feces. *Chemosphere, 84*(6), 832-839.

Mirara, W. S. (2017). *Drying and pasteurisation of vip latrine FS using a bench scale medium infrared machine.* Master of Science in Chemical Engineering, University of KwaZulu-Natal, Durban.

Mnisi, R. (2011). *An assessment of the water and sanitation problems in New Forest, Bushbuckrifdge Local Municipality, South Africa.* MSc dissertation, University of the Free State, Bloemfontein.

Mnkeni, P., & Austin, L. (2009). Fertiliser value of human manure from pilot urine-diversion toilets. *Water SA, 35*(1), 133-138.

Modinger, F., & Mayr, J. (2006). Options for the use of renewable fuels in tunnel kilns. *ZI International, 59*(8), 44-54.

Moe, C. L., & Rheingans, R. D. (2006). Global challenges in water, sanitation and health. *Journal of Water and Health, 4*(S1), 41-57.

Mohanraj, M., & Chandrasekar, P. (2009). Performance of a forced convection solar drier integrated with gravel as heat storage material for chili drying. *Journal of Engineering Science and Technology, 4*(3), 305-314.

Mühlbauer, W., Esper, A., & Muller, J. (1993, August). Solar energy in agriculture. In *ISES solar world congress, Budapest* (pp. 23-27).

Mujumdar, A. S. (2006). *Handbook of industrial drying*: CRC Press.

Muspratt, A. M., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Strande, L. (2014). Fuel potential of FS: calorific value results from Uganda, Ghana and Senegal. *Journal of Water Sanitation and Hygiene for Development, 4*(2), 223-230.

Mustayen, A., Mekhilef, S., & Saidur, R. (2014). Performance study of different solar dryers: A review. *Renewable and Sustainable Energy Reviews, 34*, 463-470.

Nikiema, J., Cofie, O., Impraim, R., & Adamtey, N. (2013). Processing of fecal sludge to fertilizer pellets using a low-cost technology in Ghana. *Environment and Pollution, 2*(4), 70.

Niwagaba, C. (2007). *Human excreta treatment technologies: prerequisites, constraints and performance.* Thesis, Department of Biometry and Engineering, Swedish University of Agricultural Sciences.

Nnadozie, R. C. (2013). Access to basic services in post-apartheid South Africa: What has changed? Measuring on a relative basis. *The African Statistical Journal, 16*, 81-103.

Nwaneri, C. F. (2009). *Physico-chemical characteristics and biodegradability of contents of ventilated improved pit latrines (VIPs) in eThekwini Municipality.* Master's dissertation, University of KwaZulu-Natal..

O'Riordan, M. (2009). Investigation into methods of pit latrine emptying. *Partners in Development, WRC Project, 1745*.

Ogheneruona, D. E., & Yusuf, M. O. (2011). Design and fabrication of a direct natural convection solar dryer for tapioca. *Leonardo Electronic Journal of Practices and Technologies, 3*, 95-104.

Ogunji, J. O., Nimptsch, J., Wiegand, C., & Schulz, C. (2007). Evaluation of the influence of housefly maggot meal (magmeal) diets on catalase, glutathione S-transferase and glycogen concentration in the liver of Oreochromis niloticus fingerling. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 147*(4), 942-947.

Okos, M. R., Narasimhan, G., Singh, R.K, & Witnaurer, A.C. (1992). Food Dehydration. In D.R. Hedman and D.B.Lund (Eds.). *Hand book of food engineering*: Marcel Dekker.

Onyegegbu, S., Morhenne, J., & Norton, B. (1994). Second law optimization of integral type natural circulation solar energy crop dryers. *Energy Conversion and Management, 35*(11), 973-983.

Pangavhane, D. R., Sawhney, R., & Sarsavadia, P. (2002). Design, development and performance testing of a new natural convection solar dryer. *Energy, 27*(6), 579-590.

Panwar, N., Kaushik, S., & Kothari, S. (2012). State of the art of solar cooking: an overview. *Renewable and Sustainable Energy Reviews, 16*(6), 3776-3785.

Perumal, R. (2007). *Comparative performance of solar cabinet, vacuum assisted solar and open sun drying methods.* Master's dissertation, McGill University, Montreal, Quebec.

Pollution Research Group. (2017). Final rttc flow sheet (18-09-2017). University of KwaZulu-Natal. Retrieved from http://prg.ukzn.ac.za/docs/default-source/presentations/final-rttc-flow-sheet_simplified---v3-(updated-12-07-2017).pdf?sfvrsn=2

Power, C. (2010). Technology roadmap: concentrating solar power. *IEA Technology Roadmaps* , International Energy Agency.

Prakash, S., Jha, S., & Datta, N. (2004). Performance evaluation of blanched carrots dried by three different driers. *Journal of Food Engineering, 62*(3), 305-313.

Rose, C., Parker, A., Jefferson, B., & Cartmell, E. (2015). The characterization of feces and urine: a review of the literature to inform advanced treatment technology. *Critical Reviews in Environmental Science and Technology, 45*(17), 1827-1879.

Ruiz-López, I. I., Córdova, A. V., Rodríguez-Jimenes, G. C., & García-Alvarado, M. A. (2004). Moisture and temperature evolution during food drying: effect of variable properties. *Journal of Food Engineering, 63*(1), 117-124.

Sachs, J. D. (2012). From millennium development goals to sustainable development goals. *The Lancet, 379*(9832), 2206-2211.

Saeed, I., Sopian, K., & Abidin, Z. Z. (2008). Drying characteristics of roselle (1): mathematical modeling and drying experiments. *Agricultural Engineering International: CIGR Journal 10.*

Sahoo, S. K. (2016). Renewable and sustainable energy reviews solar photovoltaic energy progress in India: a review. *Renewable and Sustainable Energy Reviews, 59*, 927-939.

Seck, A., Gold, M., Niang, S., Mbéguéré, M., Diop, C., & Strande, L. (2015). FS drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa. *Journal of Water Sanitation and Hygiene for Development, 5*(1), 72-80.

Serth, R. W. (2007). *Process heat transfer: principles and applications*: Elsevier Academic Press.

Sevilla, M., & Fuertes, A. B. (2009). The production of carbon materials by hydrothermal carbonization of cellulose. *Carbon, 47*(9), 2281-2289.

Sharma Sunil, S. A. (2013). Technologies for energy recovery from faecal waste - Technical and finance analysis for gasification. *Resource Recovery, 14(2),* 345-350.

Simate, I. (2003). Optimization of mixed-mode and indirect-mode natural convection solar dryers. *Renewable Energy, 28*(3), 435-453.

Singh, S., Mohan, R. R., Rathi, S., & Raju, N. J. (2017). Technology options for FS management in developing countries: Benefits and revenue from reuse. *Environmental Technology & Innovation, 7*, 203-218.

Sistani, K., Rowe, D., Miles, D., & May, J. (2001). Effects of drying method and rearing temperature on broiler manure nutrient content. *Communications in Soil Science and Plant Analysis, 32*(13-14), 2307-2316.

Sodha, M., Dang, A., Bansal, P., & Sharman, S. (1985). An analytical and experimental study of open sun drying and a cabinet tyre drier. *Energy Conversion and Management, 25*(3), 263-271.

Spinosa, L., & Vesilind, P. A. (2001). *Sludge into biosolids*: IWA publishing.

St-Hilaire, S., Sheppard, C., Tomberlin, J. K., Irving, S., Newton, L., McGuire, M. A., Sealey, W. (2007). Fly prepupae as a feedstuff for rainbow trout, Oncorhynchus mykiss. *Journal of the World Aquaculture Society, 38*(1), 59-67.

Still, D., & Foxon, K. (2012). Tackling the challenges of full pit latrines, Volume 1: Understanding sludge accumulation in VIPs and strategies for emptying full pits. *Report to the Water Research Commission* , 1745/1/12. Pretoria, South Africa.

Still, D. Foxon, K., O'Riordan, M. (2012). *Tackling the challenges of full pit latrines:* Water Research Commission, South Africa.

Strande, L., & Brdjanovic, D. (2014). *FS management: systems approach for implementation and operation*: IWA publishing.

Strauss, M., Larmie, S., & Heinss, U. (1997). Treatment of sludges from on-site sanitation-Low-cost options. *Water Science and Technology, 35*(6), 129-136.

Thiagarajan, I. V. (2008). *Combined microwave-convection drying and textural characteristics of beef jerky*. Thesis, University of Saskatchewan, Saskatoon, South Africa.

Thirugnanasambandam, M., Iniyan, S., & Goic, R. (2010). A review of solar thermal technologies. *Renewable and Sustainable Energy Reviews, 14*(1), 312-322.

Tilley, E. (2008). *Compendium of sanitation systems and technologies*: Eawag Aquatic Research.

Timilsina, G. R., Kurdgelashvili, L., & Narbel, P. A. (2012). Solar energy: markets, economics and policies. *Renewable and Sustainable Energy Reviews, 16*(1), 449-465.

Tiwari, G., & Ghosal, M. (2005). *Renewable energy resources: basic principles and applications*: Alpha Science Int'l Ltd.

Toğrul, İ. T., & Pehlivan, D. (2003). Modelling of drying kinetics of single apricot. *Journal of Food Engineering, 58*(1), 23-32.

Tomar, V., Tiwari, G., & Norton, B. (2017). Solar dryers for tropical food preservation: Thermophysics of crops, systems and components. *Solar Energy, 154*, 2-13.

Treybal, R. E. (1980). *Mass transfer operations*: McGraw-Hill.

Tyagi, V., Rahim, N. A., Rahim, N., Jeyraj, A., & Selvaraj, L. (2013). Progress in solar PV technology: research and achievement. *Renewable and Sustainable Energy Reviews, 20*, 443-461.

Udert, K. M., Buckley, C. A., Wächter, M., McArdell, C. S., Kohn, T., Strande, L., Etter, B. (2015). Technologies for the treatment of source-separated urine in the eThekwini Municipality. *Water SA, 41*(2), 212-221.

United Nations Development Programme. (2000). *World energy assessment: energy and the challenge of sustainability*: UNDP.

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects: future prospects for food and feed security*: Food and Agriculture Organization of the United Nations.

Vega, A., Fito, P., Andrés, A., & Lemus, R. (2007). Mathematical modeling of hot-air drying kinetics of red bell pepper (var. Lamuyo). *Journal of Food Engineering, 79*(4), 1460-1466.

Veriansyah, B., & Jae-Duck, K. (2007). RETRACTED: Supercritical water oxidation for the destruction of toxic organic wastewaters: A review: Elsevier.

Vinnerås, B., Palmquist, H., Balmér, P., & Jönsson, H. (2006). The characteristics of household wastewater and biodegradable solid waste—a proposal for new Swedish design values. *Urban Water Journal, 3*(1), 3-11.

Walker, J., & Duncan, G. (1974). Effectiveness of recommended greenhouse air circulation systems. *Transactions of the ASAE, 17*(2), 371-0374.

Werther, J., & Ogada, T. (1999). Sewage sludge combustion. *Progress in Energy and Combustion Science, 25*(1), 55-116.

WHO. (2015). Key facts from JMP 2015 report. Retrieved 12-09-2017 http://www.who.int/water_sanitation_health/monitoring/jmp-2015-key-facts/en/

WHO & UniCeF. (2014). *Progress on sanitation and drinking water: 2014 update*: World Health Organization.

Williams, P. T. (2013). *Waste treatment and disposal*: John Wiley & Sons.

Winker, M., Vinnerås, B., Muskolus, A., Arnold, U., & Clemens, J. (2009). Fertiliser products from new sanitation systems: their potential values and risks. *Bioresource Technology, 100*(18), 4090-4096.

Zawilska, E., & Brooks, M. (2011). An assessment of the solar resource for Durban, South Africa. *Renewable Energy, 36*(12), 3433-3438.

Zuma, L., Velkushanova, K., & Buckley, C. (2015). Chemical and thermal properties of VIP latrine sludge. *Water SA, 41*(4), 534-540.

APPENDIXES

Appendix A: Ethical clearance

UNIVERSITY OF KWAZULU-NATAL

INYUVESI YAKWAZULU-NATALI

RESEARCH OFFICE
BIOMEDICAL RESEARCH ETHICS ADMINISTRATION
Westville Campus
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Durban
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Tel: 27 31 2604769 - Fax: 27 31 260-4609
Email: BREC@ukzn.ac.za
Website: http://research.ukzn.ac.za/ResearchEthics/BiomedicalResearchEthics.aspx

03 April 2017

Mr TR Mugauri (212545105)
Discipline of Chemical Engineering
College of Agriculture, Engineering and Science
tendayimugauri@yahoo.co.uk

Dear Mr Mugauri

Title: Drying and pasteurization of faecal sludge using solar Thermal energy. Or solar drying of faceal Sludge.
Degree: MSc
BREC Ref No: EXM200/17

I refer to your application to BREC received on 22 March 2017 and wish to advise that exemption of ethics review is granted for this study.

This exemption will be noted at the next Biomedical Research Ethics Committee meeting to be held on 11 April 2017.

Yours sincerely

Professor J Tsoka-Gwegweni
Chair: Biomedical Research Ethics Committee

Appendix B: Drying chamber drawings

The construction drawings were drawn using SolidWorks and transposed to produce construction drawings.

Figure B. 1: Drawing #1

Figure B. 2: Drawing #2
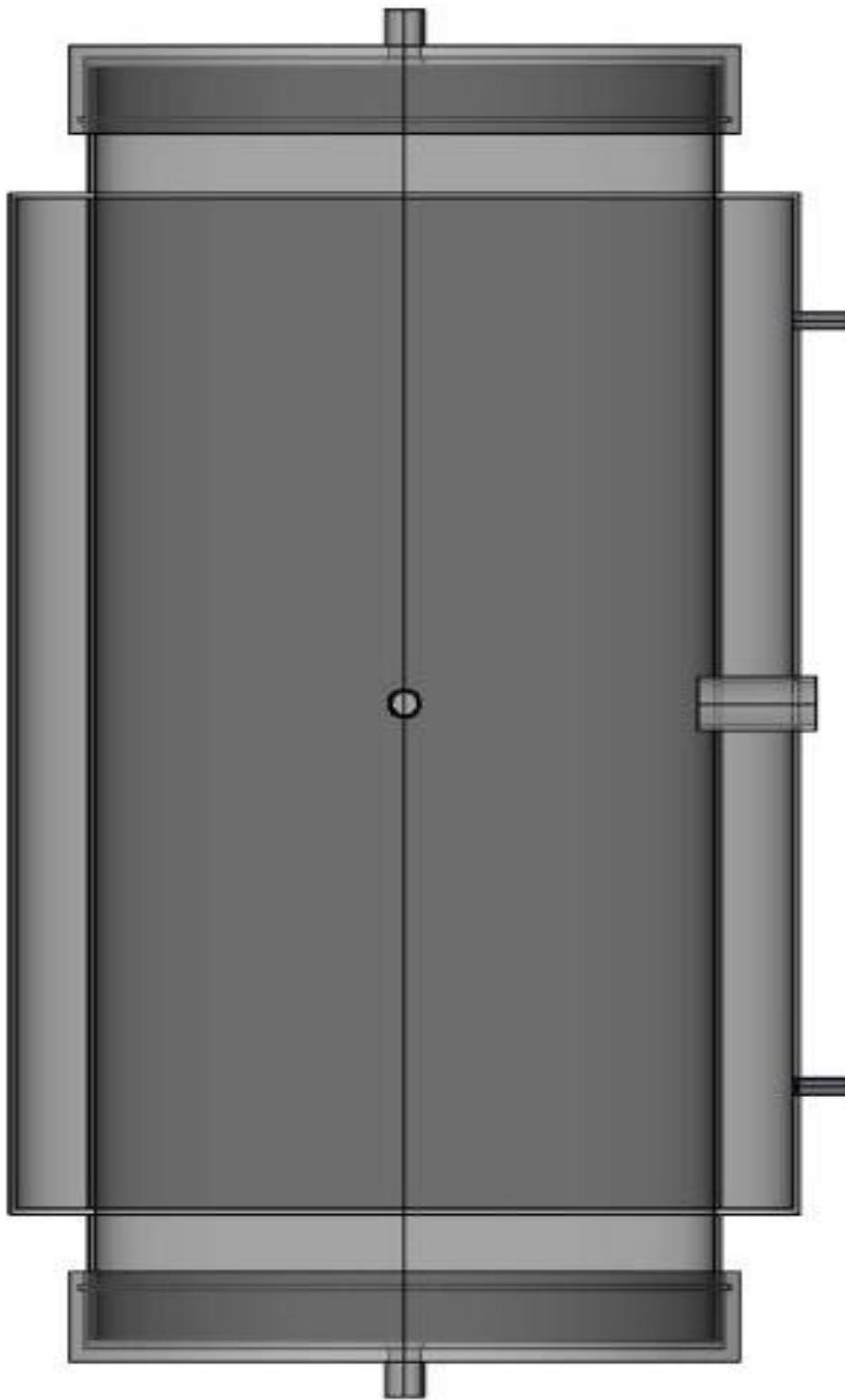
Figure B. 3: Drawing #3
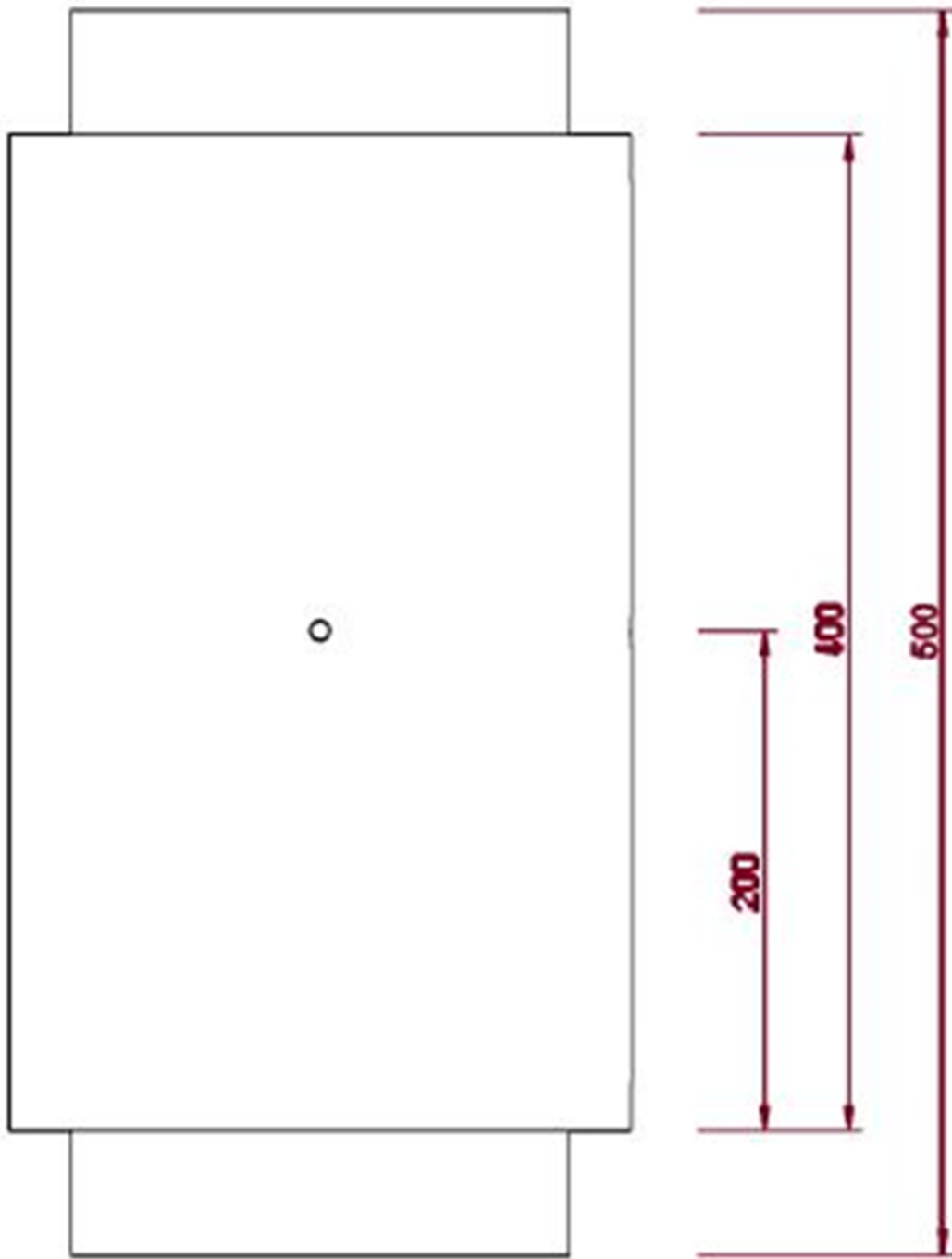
Figure B. 4: Drawing #4
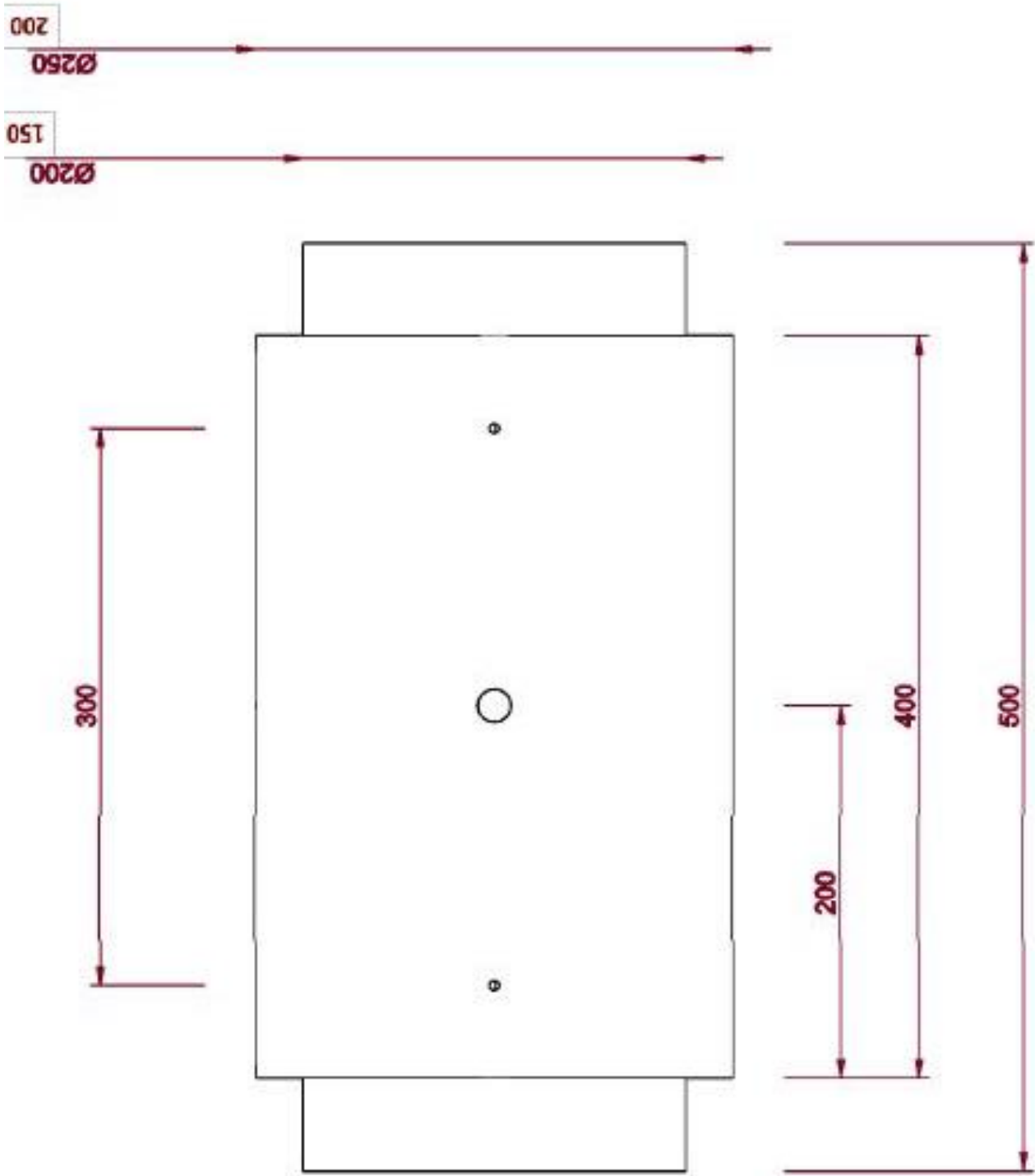
Figure B. 5: Drawing #5

Appendix C: Standard operating procedures

C1: Drying Rig

1. Scope and Application

Drying is a mass transfer process consisting of the removal of a solvent by evaporation from a solute. The process involves a heat source and a carrying medium to absorb and transport the moisture away. In the most common case, a gas stream is used to apply the heat by convection and carry away the vapor. When a piece of wet material is exposed to unsaturated air, evaporation takes place from its surface. The rate of evaporation is higher with an increase in temperature of the air. At a given temperature the rate of evaporation is dependent on the vapor pressure difference between the air close to the material and that of the more mobile air surrounding it. The drying rig allows control of a preheated air temperature and flow rate.

2. Brief description of the Rig

A compressed air line is used to drive the flow through the rig. The flow rate is controlled by use of a valve on the compressed air line and monitored by a rotameter. A heater is also connected to control the temperature of the air stream. The sample is exposed to direct solar radiation in a double walled transparent drying box. The radiation is measured on site by use of a pyranometer.

3. Safety Precautions

Ensure that all electric cables are not in contact with water.

Do not switch on the heater when there is no air flow.

Ensure all pipes are firmly connected

4. Procedure

Start up

1. Switch on computer and open appropriate software (Solar Drying) and data logger

2. Test and preset the flowrate

3. Preheat air to desired temperature

4. Switch on mass balance and pyranometer

5. Place sample in the drying chamber

Operation

1. Log and monitor rotameter regularly

Shut down

1. Remove sample, Switch off the mass balance and pyranometer

2. Switch off the heater

3. Close the air supply

4. Turn off the computer and data logger

Cleaning and Disinfecting

1. Remove holder from drying rig mass support

2. Clean holder with sponge

3. Disinfect holder and sore away for future use

5.0 Maintenance

Part/Apparatus	Brand Name	Model Number	Sensitivity	Special Notes
Mass Balance	BOECO	BPS51 plus	0-4500g 10mg (2dp) Max op temp = 500C	Recalibrate weekly
Rotameter	Tecfluid	PS-31/PVC	0-30l/s Max op Temp = 600C	
Pyranometer and amp box	Kipp and Zonen	CMP3	0-2000w/m2	

C2: Ash and moisture content (total and volatile solids)

Introduction

Solids refer to matter suspended or dissolved in water, wastewater and fecal sludge. Solids may affect water or effluent quality adversely in a number of ways. Solids analyses are important in the control of biological and physical wastewater treatment processes and for assessing compliance with regulatory agency wastewater effluent limitations.

Total Solids is the term applied to material residue left in the vessel after evaporation of a sample and its subsequent drying in an oven at a defined temperature. Total solids includes total suspended solids, the potion of solids retained by a filter and total dissolved solids, the portion that passes through the filter of 2.0um or smaller. Fixed Solids, is the term applied to residue of total, suspended or dissolved solids after heating to dryness for a specified time at a specified temperature. The weight loss on ignition is called volatile solids.

Moisture content dried at 103-105ºC
1. Scope and Field of Application

Total Solids are determined in a wide variety of liquid and semi-liquid materials. These include portable waters, domestic and industrial waters, polluted waters and FS produced from treatment processes. It is of particular importance for the efficient operation of a treatment plant.

A known volume of well-mixed sample is evaporated to dryness in a porcelain crucible in a hot air oven at 105ºC, the solids remaining are cooled and weighed. The residual material in the crucible is classified as total solids, and may consist of organic, inorganic, dissolved, suspended or volatile matter

2. Interferences
- Highly mineralized water with a significant concentration of calcium, magnesium, chloride and sulphate may be hygroscopic and require prolonged drying, proper desiccation and rapid weighing.
- Exclude large, floating particles from the sample if it is determined that their inclusion is not desired in the final result.
- Disperse visible floating oil and grease with a blender before withdrawing sample portion for analysis because excessive residue in the dish may form a water-trapping crust.

3. Sampling
- Mix the sample well to suspend solids uniformly.
- Remove the test portion rapidly before any settling of solid matter occurs.
- Use a measuring cylinder and not a pipette for sludge and wastewater samples.
- Use a crucible for faeces.
- Use a volume or mass of sample to ensure a measurable residue- limit sample to no more than 200mg residue
- Suitable aliquots: Liquid samples – 100ml, Sludge -30ml, Faeces 10-20g

4. Safety Precautions
- Always use safety goggles, gloves and laboratory coat while working in laboratory
- Wear gloves suitable for withstanding high temperatures when removing crucibles from the oven.
- After the analysis clean bottles and beakers with clear water keep it for drying
- Dispose the used gloves after completion of analysis
- Clean the hands using antiseptic soap
- Disinfect hands after washing with soap
- Avoid spillage and contact with skin. In the latter case use copious washings with cold water and call for medical attention.

5. Apparatus
- 50ml capacity evaporating porcelain crucibles
- Desiccator
- Drying oven
- Analytical Balance

6. Reagents
- None

7. Calibration
- Check the temperature throughout the oven area by placing a calibrated thermometer on each shelf, after 30mins, check temperature at each level against oven setting.
- Adjust oven setting if necessary.
- If temperatures are uneven on the shelves, check insulation.

8. Procedure
Prepare Crucible
- If volatile solids are to be measured ignite clean crucible at 550ºC for 1hr in the furnace. If only total solids are to be measured, heat clean crucible to 103-105ºC for 1h. Store and cool dish in a desiccator until needed. Weigh immediately before use**…….W_1g**

Sample Analysis
- Measure out appropriate volume (30ml) /minimum mass (10-20g) that will yield a residue between 2.5 and 200mg of a mixed sample using correct volume measuring cylinder or analytical balance**….Vml…Wg**. Transfer quantitatively to the weighed crucible, rinsing the cylinder with small volumes of distilled water to dislodge heavy particles. Add washings to the crucible.
- Place in hot oven at 103-105°C for 24hrs.

- Dry sample for at least 1hr in an oven 103-105°C, to desiccator to balance temperature and weigh. Repeat cycle of drying, cooling and weighing until a constant weight is obtained, or until weight change is less than 4% of previous weight or 0.5mg, whichever is less.
- Remove the next day and cool for 15 minutes and weigh**…..W$_2$g**

9. Calculation

$$Total\ Solids\ in\ Sample\ (mg/l) = \frac{(W_2 - W_1)g \times 100\ 000}{V_{sample}\ (ml)}$$

$$Total\ Solids\ in\ Wet\ Sample\ (g/g) = \frac{(W_2 - W_1)g}{W_{sample}\ (g)}$$

$$Moisture\ Content\ (g) = W_{sample}(g) - [(W_2 - W_1)]g$$

Ash Content Ignited at 550ºC

1. Principle

The residue from the above methods is ignited to constant weight at 550ºC. The remaining solids represent the fixed total, dissolved or suspended solids while the weight lost on ignition is the volatile solids. The determination is useful in control of wastewater treatment plant operation because it offers a rough estimate of the amount of organic matter present in the solid fraction of wastewater, activated sludge and industrial wastes.
Interferences:
- Negative errors in the volatile solids may be produced by loss of volatile matter during the drying.

2. Apparatus
- Muffle Furnace
- As above

3. Procedure
- Ignite residue from the total solids to constant weight in a muffle furnace at a temperature of 550ºC.
- Have furnace up to temperature before inserting sample.
- Usually 2 hr for VIP and sludge samples,15-20min for wastewater (200mg residue)
- Let the crucible cool partially in air until most of the heat has dissipated
- Transfer to a desiccator for final cooling. Do no overload the desiccator
- Weigh dish as soon as it has cooled to balance temperature.

5. Calculation

$$Volatile\ Solids\ in\ Wet\ Sample\ (g/g) = \frac{(B - C)}{W_{sample}(g)}$$

$$Volatile\ Solids\ in\ Dry\ Sample\ (g/g) = \frac{VS_{wet\ sample}}{Total\ Solids(g/g)}$$

$$Fixed\ Solids\ in\ Wet\ Sample(g/g) = \frac{(C - D)}{W_{sample}(g)}$$

$$Fixed\ Solids\ in\ Dry\ Sample\ (g/g) = \frac{FS_{wet\ sample}}{Total\ Solids\ (g/g)}$$

B = weight of residue + crucible before ignition - 550ºC (g)
C = weight of residue + crucible after ignition -550ºC (g)
D = weight of crucible (g)

C3: Nutrient analysis

1. Scope and Application,
· Test measures the nitrite concentration in the range 1.0 – 90 mg/l NO_2-N.
· Test measures both ammonium ions and dissolved ammonia in a concentration range of 2 – 150 mg/l NH4-N.

2. Summary
· In acidic solution nitrite ions react with iron(II) ethylenediammonium sulphate to form a yellow to green-brown iron(II) compound that is determined photometrically.
· Ammonium nitrogen (NH4-N) occurs partly in the form of ammonium ions and partly as ammonia.
· A pH dependent equilibrium exists between the two forms.
· In strongly alkaline solutions, NH4-N is present almost entirely as ammonia, which reacts with hypochlorite ions to form monochloramine.
· This in turn reacts with a substituted phenol to form a blue indophenol derivative that is determined photometrically.

3. Apparatus and Glassware
· Spectroquant.
· Reaction cells.
· Pipette.
· Rectangular cells 10 mm (2 pcs), Cat. No. 114946.

5. Collection, Preservation and Storage
· Collect faecal samples in 1L plastic buckets.
· Preferably, analyse samples immediately after sampling.
· Store samples at 4 °C or freeze dry samples.
· Preserve wastewater samples by acidifying with concentrated sulphuric acid to pH 2 and faecal samples by freeze drying or freezing.
· Determine NO2-N on well- homogenised samples.
· Samples containing more than 90.0 mg/l NO2-N must be diluted with distilled water.
· The pH must be within the range 1 - 12. Adjust, if necessary, with sulfuric acid.
· Filter turbid samples.

6. Safety Precautions
· Handle concentrated acid with care.
· Always use safety goggles, gloves and laboratory coat while working in laboratory.
· Wear face shield and protect hands from heat produced when contents of the vessels are mixed.After the analysis, clean bottles and beakers with clear water keep it for drying.
· Dispose the used gloves after completion of analysis.

- Clean the hands using antiseptic soap.
- Disinfect hands after washing with soap.
- Avoid spillage and contact with skin. In the latter case use copious washings with cold water and call for medical attention.

7. Sample Preparation –FS

1. Weigh out 2.0000g of well-mixed FS sample.
2. Blend the weighed sample with 500ml of distilled water in a 1L blender for 30 seconds on the highest speed.
3. Add 250ml distilled water and blend on highest speed until the sample is homogenised (this could range from 30 to 60 seconds).
4. Transfer the blended mixture into a 1L volumetric flask.
5. Add 200ml of blender washings into the flask and top up to 1L with distilled water.
6. Transfer the 1L solution to a plastic bottle and store at 4 °C.

8. Reagents

- Reagent NO2-1K.
- Universal indicator strips pH 0-14.
- pH indicator strips, pH 0-6.
- Sulphuric acid 0.5 mol/l.

9. Calibration

- To check the photometric measurement system (test reagents, measurement device, handling) and the mode of working, use the nitrite solution 40 mg/l NO2-N.
- Prepare a series of at least three standards, covering the desired range, and a blank by diluting suitable volumes of standard solutions. Prepare a calibration curve by plotting instrument response against standard concentration. Compute sample concentration by comparing sample response with the standard curve. Multiply answer by appropriate dilution factor. Report only those values that fall between the lowest and the highest calibration standards. Dilute and reanalyse amples exceeding the highest standard. Report results in mg/L.

10. Procedure

• Place 2 level blue micro spoons of reagent NO2-1K in a reaction cell.

- Pipette 8.0 ml of pre-treated sample into the reaction cell, close the cell and shake until the reagent is completely dissolved.
- Leave to stand for exactly 20 minutes, then measure the sample in the photometer. Do not shake or swirl the cell before the measurement.

Notes on the measurement:

- For photometric measurement, the cells must be clean. Wipe, if necessary, with a clean dry paper towel.
- Measurement of turbid solutions yields false-high readings.
- The pH of the measurement solution must be within the range 1.2 - 1.6.
- The colour of the measurement solution remains stable for only a short time after the end of the reaction time stated above.

11. Waste Disposal

- Collect waste in a 2.5L bottle for collection from Waste Tech.

C4: Thermodynamic properties

Thermal Conductivity.

1. Scope and Application

- This document provides instructions on testing minimal volumes of powder, liquids, faeces, pit latrine (VIP) samples using TCi small volume test kit (SVTK).
- Testing with the C-Therm TCi can directly measure thermal conductivity and thermal effusivity.
- It can indirectly measure diffusivity, heat capacity, the R-value or depth of penetration.

2. Summary
- The SVTK was developed for testing minimal volumes of liquid volumes of fluid material.
- Reducing the volume of sample material required for an effective thermal conductivity measurement is extremely important in the testing of energetic materials whereby larger samples pose a significant safety concern.
- The use of the accessory has also been applied widely in the testing of various materials that are doped with extremely expensive filters (gold, diamonds etc.) that are in limited supply.

3. Apparatus
SVTK P/N:
- Weight
- Test Cell, Allen screws,
- TCi sensor
- Sensor Base
- Measuring spoons(1/8 and ¼)

4. Reagents
- No reagents are used.

5. Interferences
- If any cell is red, the measurement is not valid. Repeat the measurement.
- Check the R2 value for each measurement. If the R2 value is less than 0.995, the measurement is not valid.
- An orange cell means that the thermal conductivity or thermal effusivity value is outside of the calibration range of that material group.
- To enter density: Click on material, add, density value, save.

6. Collection, Preservation and Storage
- Collect samples in 1L plastic buckets.
- Preferably, analyse samples immediately after sampling.
- Store samples at 4 °C or freeze dry samples.
- Preserve wastewater samples by acidifying with concentrated sulphuric acid to pH 2 and faecal samples by freeze drying or freezing.
- Determine COD on well- homogenized samples.

7. Safety Precautions
- Always use safety goggles, gloves and laboratory coat while working in laboratory
- Wear gloves suitable for withstanding high temperatures when removing crucibles from the oven.
- After the analysis clean bottles and beakers with clear water keep it for drying
- Dispose the used gloves after completion of analysis
- Clean the hands using antiseptic soap
- Disinfect hands after washing with soap
- Avoid spillage and contact

8. Calibration
- Sensor is factory calibrated. Calibration data is stored on the sensor chip.
  i. USER ID: Admin
  ii. Password: no password

9. Procedure

Density:
- Weigh out X3 1/8 teaspoon of sample and divide by the total volume (1.8ml).
- Enter density value in table.
- Go to Test details/ material l (…) enter density value. Press + for addition of density for another test.
- Save and close.

Solid testing:
- Fill the 1/8 teaspoon (0.63ml) with the sample to be investigated.
- Level off the excess sample by scraping off the excess with a spatula by making a horizontal movement.
- Care must be taken to prevent compaction of the sample in the teaspoon (e.g. Vibrations, rearranging sample with spatula, and tapping on the teaspoon).
- The sample remaining in the teaspoon is the specimen.
- Transfer the sample to a weighing dish.
- Repeat the above steps 3 times for a total volume of specimen of approximately 3/8 teaspoon or 1.8ml.
- Place the weight onto the sample so that it seats on the rim of the test cell. NB: If the sample to be measured weighs more than 150g, omit the weight.
- Monitor the sensor temperature via the TCi software until it is stable and the sensor, sample and environment have all reached a state of thermal equilibrium.
- Initiate the test sequence within the TCi software.
- Alter test measurements to enter the number of measurements required (usually 5 measurements are required).

Cleaning:
- Pour out the contents of the sample from the test cell or remove it with a paper towel.
- Place sensor upside down and remove the test cell by gradually unfastening the three screws in a sequenced manner. Use a 3/32 Allen wrench.
- Remove the sensor test and clean with either soap and water, water or propyl alcohol.
- To test again place the test cell on the sensor and place upside down in order to have easy access to the screws.
- Tighten gradually and in sequence until the test cell seats perfectly flat against the sensor-housing surface.

Liquid testing:
- Measure 1.25ml (1/4 tsp) of total liquid volume of specimen.
- Transfer this volume directly to the test cell.
- Place the quick clamp cap on the test cell.
- Use of the cap is optional, but will prevent any undesirable evaporation of the liquid from the cell.
- Monitor the sensor temperature via the TCi software until it is stable and the sensor, sample and environment have all reached a state of equilibrium.
- Initiate the test sequence within the TCi software.

Reports:
- Click on Reports/test report/enter test number or additional details /search/export report/open folder/save.

CALORIMETRIC TESTS.

1. Scope and Application
- Heats of combustion as determined in an oxygen bomb calorimeter are measured by a substation procedure in which the heat obtained from the sample is compared with the heat obtained from combustion of a similar amount of benzoic acid or other standardizing material whose calorific value is known.
- These measurements are obtained by burning a representative sample in a high pressure oxygen atmosphere within a bomb.
- The energy released by this combustion is absorbed within the calorimeter and the resulting temperature change within the absorbing medium is noted.
- The heat combustion of the sample is then calculated by multiplying the temperature rise in the calorimeter by the previously determined energy equivalent or heat capacity determined from a standardizing material.

2. Summary
- Calorimetry is the science of measuring quantities of heat, as distinct from temperature. The instruments used for such measurements are known as calorimeters. The oxygen bomb calorimeters, which are the standard instruments for measuring calorific values of liquid and solid combustible samples.
- The calorific value (heat of combustion) of a sample may be broadly defined as the number of heat units liberated by a unit mass of a sample when burned with oxygen in an enclosure of constant volume.

3. Apparatus
- Parr 6200 oxygen bomb calorimeter.
- 1180P oxygen combustion bomb
- Bomb head support stand

4. Reagents
- Benzoic acid tablets for standardization (should always be tested in pellet form).
- Ethylene glycol– combustion aid. Heat combustion= 4033cal/g. Mass (0.2160g= 4drops)

5. Sampling
- Dry sample for 24 hours at 105°C in a crucible.
- Grind dried sample to a powder form.
- Weigh out a gram of sample into the sample vial (0.5- 0.7g for faecal matter).
- The bomb should never be charged with a sample, which will release more than 8000 calories when burned in oxygen, and the initial oxygen pressure should never exceed 40 atmospheres (590 psi).
- Never charge the bomb with more than 1g of combustible material.

6. Safety Precautions
- Do not use to much sample (<1g).
- The standard bomb 1108 cannot be expected to withstand the effects of combustible charges which liberate more than 8000 calories frequently.
- This generally limits the total weight of combustible material (sample plus combustion aid) to not more than 1.1gram.
- Do not charge the bomb with more oxygen that is necessary to obtain complete combustion.
- It is best to use the lowest gas pressure that will give complete combustion.
- Lower gas pressure permit higher gas temperatures and greater turbulence, both of which help to secure better combustion. lThe range is 20- 35 atmospheres. Regulator set at 400psi (3000kpa).

- Keep all parts of the bomb-especially the O-rings, insulated electrode assemblies and valves-in good repair at all times.
- Do not fire the bomb if gas bubbles are leaking from the bomb when it is submerged in water.
- Stand back from the calorimeter for at least 15 seconds after firing and keep clear of the top of the calorimeter.
- If the bomb should explode, it is likely that the force of the explosion will be directly upward.
- SPIKE SETTING
- Spike control/ Spiking on/ Spike fixed/ 0.2160g

7. Procedure

1. Open oxygen gas cylinder, flow rate is already set to (400psi-3000kpa), do not alter.
2. Check that distilled water chamber is filled to the mark.
3. Turn on the calorimeter and activate the pump and heater.
4. Allow at least 20 minutes for the calorimeter to warm up and the jacket temperature to stabilise at 29°C.
5. The calorimeter is ready to begin testing.
6. The START key will be available at this time.
7. Fill the calorimeter bucket with 2L of distilled water.
8. Set the bucket in the calorimeter.
9. Sample prep:
   - 0.5g 24 hours at 105°C dried blended sample into capsule.
   - Tie cotton tread which is used as a fuse to ignite the sample onto heat wire in the bomb.
   - Cotton tread should not be immersed in the sample.
   - Slightly above the sample.
   - For wet samples (80% moisture content), add 4 drops of ethylene glycol to the sample before combustion.
   - When contact is made through the heating wire, the tread will ignite, drop into the sample cup and ignite the sample.
10. Care must be taken when moving the bomb head from the support stand to the bomb cylinder.
11. Moisten the base of the bomb with a few drops of water.
12. Check the sealing ring to be sure it is in good condition and moisten it with a bit of water so it will slide freely into the cylinder and push it as far down as it can go.
13. Close the bomb and pressurize with oxygen.
14. The pressure connection to the bomb is made with a slip connector on the oxygen hose.
15. Slide the connector onto the inlet valve body and push it as far as it can go.
16. Press the O_2 FILL button and step back until bomb is filled. Takes 1 minute.
17. Remove the gas connection and attach the lifting handle to the two holes in the side of the screw cap and lower the bomb into the water partially.
18. Press the banana plugs onto the two ignition wires firmly into the terminal sockets on the bomb head before the head is completely immersed in water.
19. **Note:** If bubbles continue to rise from the bomb after the air in the screw cap has escaped the test must be stopped.
20. Do not fire the bomb until the leak has been corrected.
21. Close the calorimeter cover. This lowers the stirrer and thermistor probe into the bucket.
22. Make sure that the bucket thermistor does not touch the bucket or the bomb when the lid is lowered.
23. Select determination under OPERATING MODE.
24. After pressing the START key, the calorimeter will prompt the operator for BOMB ID number, sample
25. ID number, sample weight and spike weight.
26. The calorimeter will now take over and conduct the test.
27. During the time it is establishing the initial equilibrium, the status bar will display PREPERIOD.

28. Just before it fires the bomb, at about 12 minutes, it will sound a series of short beeps to warn the user to move away from the calorimeter.
29. Once the bomb has been fired the status bar will display POSTPERIOD.
30. Read of calorific value from screen.
31. Remove the bomb from the chamber after 3 minutes and depressurize bomb by opening the valve knob slowly. After all the pressure has been released, unscrew the cap and lift the head straight out to avoid sticking.
32. Remove the chamber containing the ash.
33. Wipe the inside of the bomb clean and proceed with next sample.
34. Maintenance must be carried out after every 30 tests. Replace O-ring and wire.
35. Clean the bomb and soak in citric acid solution overnight or whenever the bomb is dirty.
36. Aqua regia can also be used to clean the bomb_ remove the wire if it is being used.

8. Calibration

- · 1 gram benzoic acid tablets are used for calibration.
- · Always use the tablets in a pellet form.
- · The heat capacity should be +/- 26 MJ/kg.

Full detailed standard operating procedures with other tests for the various analysis are available from http://prg.ukzn.ac.za/laboratory-facilities/standard-operating-procedures.

Appendix D: Experiments in replicates

Table D. 1: Key for reference on graph and sample titles and differentiation

Key	0.5m/s-S-0°C-SD-10mm-60mm	Flowrate-weather-preheating-drying mode- thickness-surface diameter
	Weather	S- Sunny
		C- Cloudy
		O-Overcast
	Drying mode	SD-Solar Drying
		OASD- Open Air Sun Drying
	N/A	Not Applicable

Table D. 2: Summary of sample, solar irradiance, drying, surface and core temperatures

Sample	Solar irradiance (W/m²)		Drying temperature (ºC)		Surface temperature (ºC)		Core temperature (ºC)	
	Range	Average	Range	Average	Range	Average	Range	Average
0.5m/s-S-0°C-SD-5mm-60mm	1400-100	978	18-35	32	20-40	29	22-35	30
	1250-200	804	15-33	31	20-45	29	20-45	29
0.5m/s-C-0°C-SD-5mm-60mm	1250-300	560	15-40	34	15-35	31	12-36	33
	900-150	310	20-28	25	10-22	16	12-20	17
0.5m/s-O-0°C-SD-5mm-60mm	600-50	100	15-20	18	11-20	14	10-18	12
	800-70	200	17-25	23	12-24	20	10-22	18
0.5m/s-S-0°C-SD-10mm-60mm	1375-300	1025	20-35	31	18-35	32	18-45	33
	1350-150	950	18-31	30	18-35	31	20-40	30
0.5m/s-S-30°C-SD-5mm-60mm	1350-200	980	18-40	33	20-40	35	18-50	34
	1400-750	1160	20-40	38	20-42	37	15-50	39
0.5m/s-S-60°C-SD-5mm-60mm	1100-300	940	20-65	60	20-80	57	20-80	59
	1400-150	1000	25-65	59	25-80	58	25-80	56

0.5m/s-S-0°C-SD-5mm-120mm	1350-250	1050	25-42	40	25-50	44	25-50	43
	1400-500	970	20-45	38	20-45	40	20-50	40
0.0m/s-S-0°C-SD- 5mm-60mm	1300-550	990	20-45	37	25-50	40	18-50	42
	1200-600	1050	25-40	35	20-40	35	20-50	40
1.0m/s-S-0°C-SD-5mm-60mm	1350-500	1000	22-40	35	18-40	35	18-40	34
	1400-450	1050	20-40	33	15-40	33	20-40	31

D1: Mass ratio variation
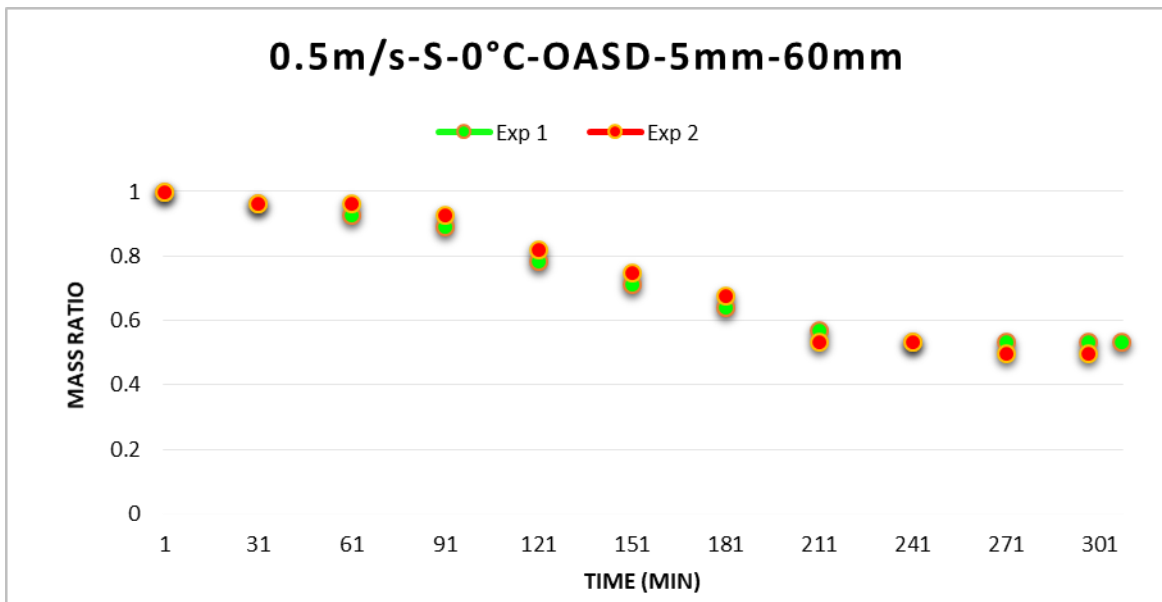
Figure D1. 1: Open air sun drying sunny conditions
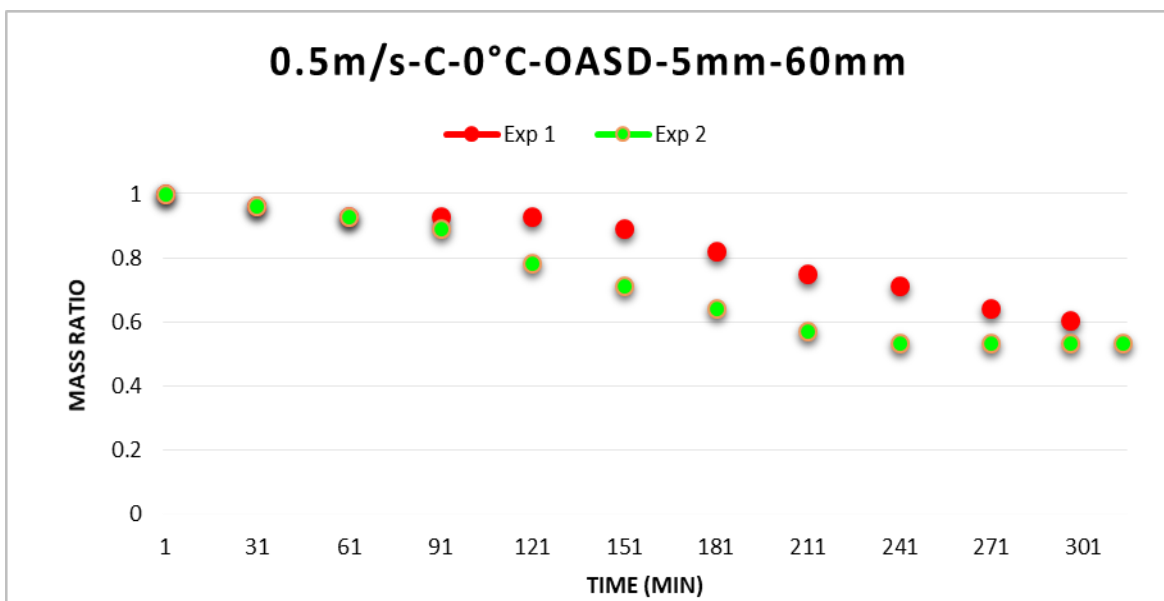
Figure D1. 2: Open air sun drying cloudy conditions
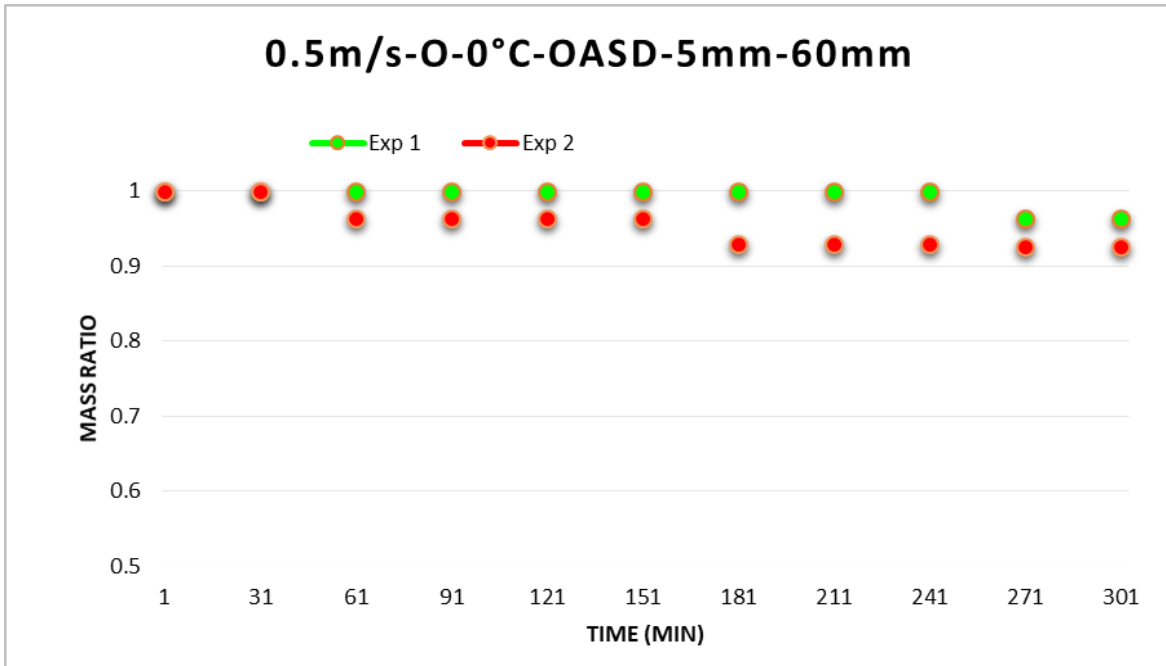
Figure D1. 3: Open air sun drying overcast conditions
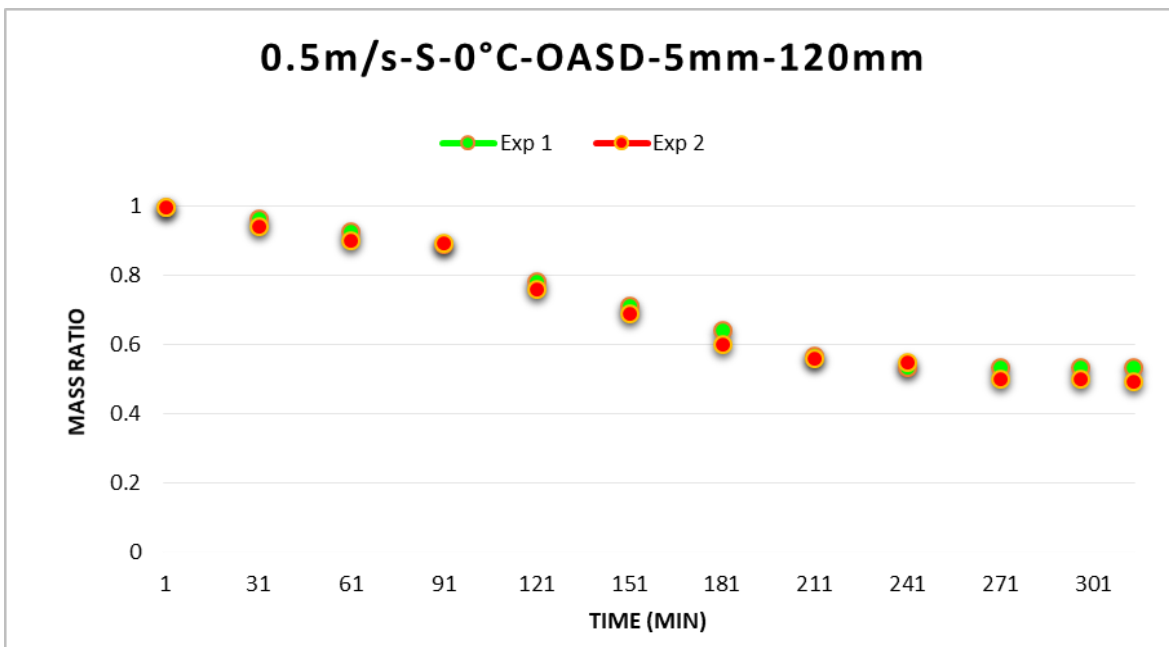
Figure D1. 4: Open air sun drying 120 mm surface diameter
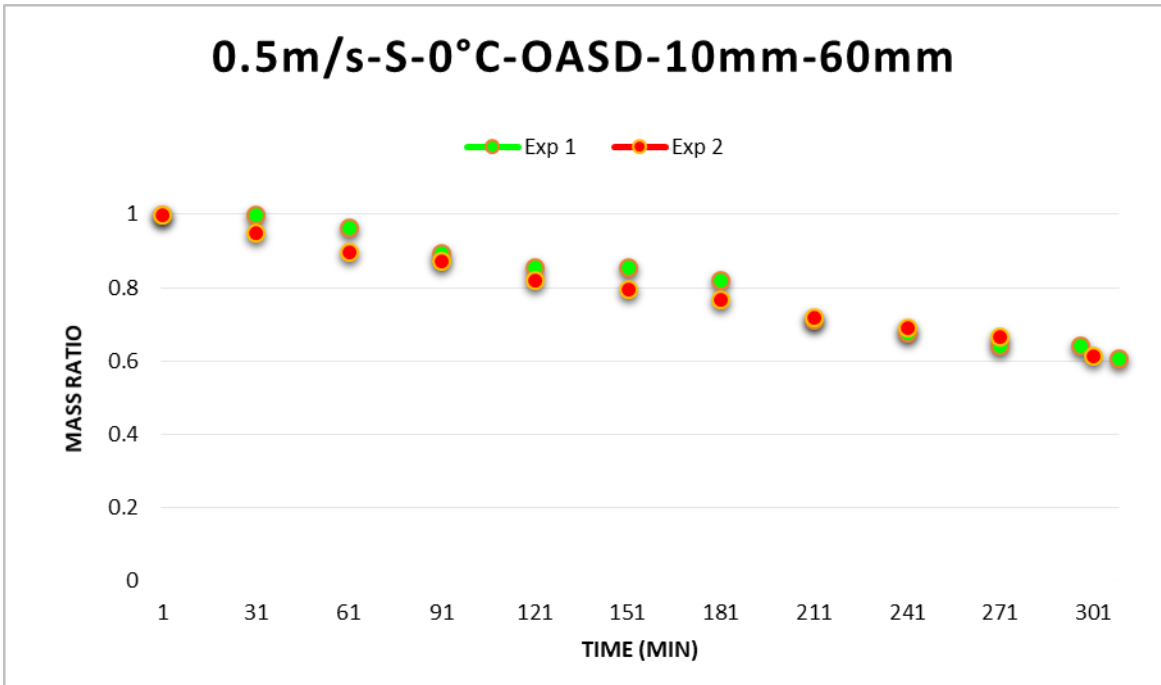
Figure D1. 5: Open air sun drying 10 mm thickness
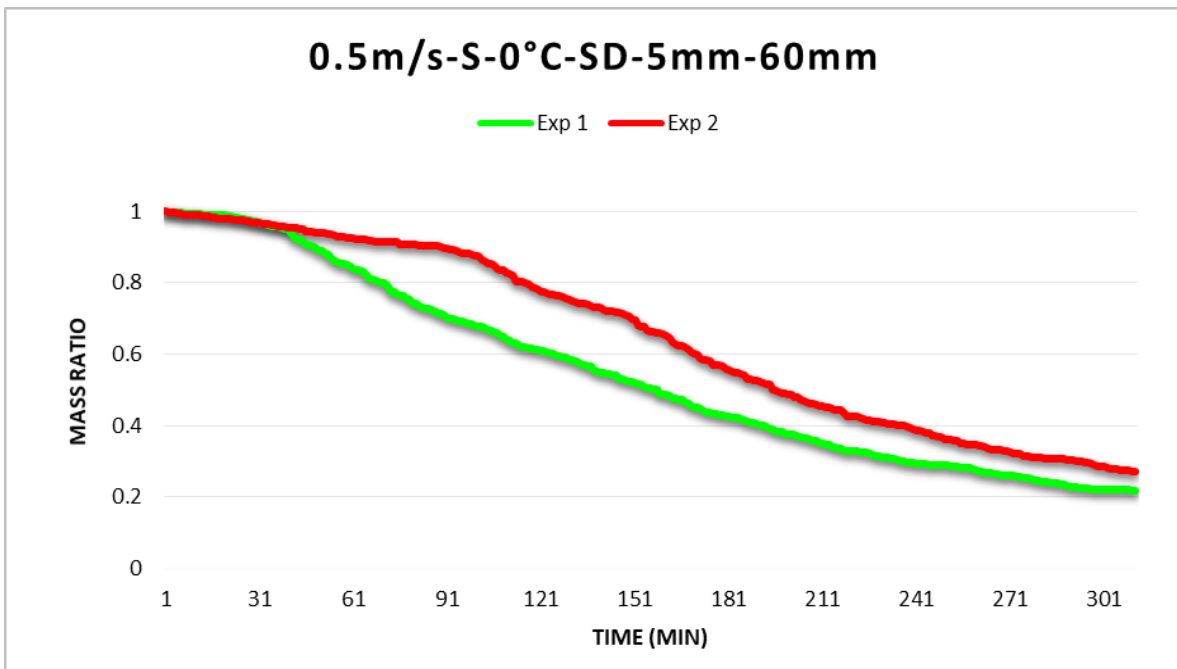
Figure D1. 6: Solar drying sunny conditions
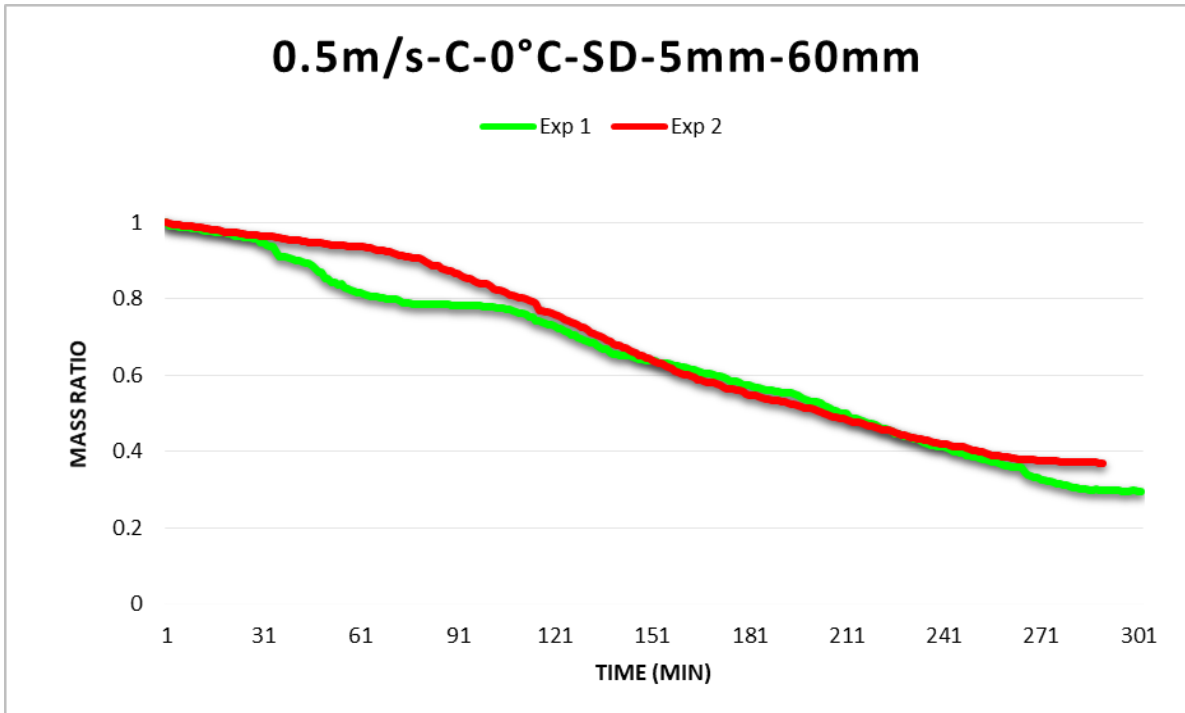
Figure D1. 7: Solar drying cloudy conditions
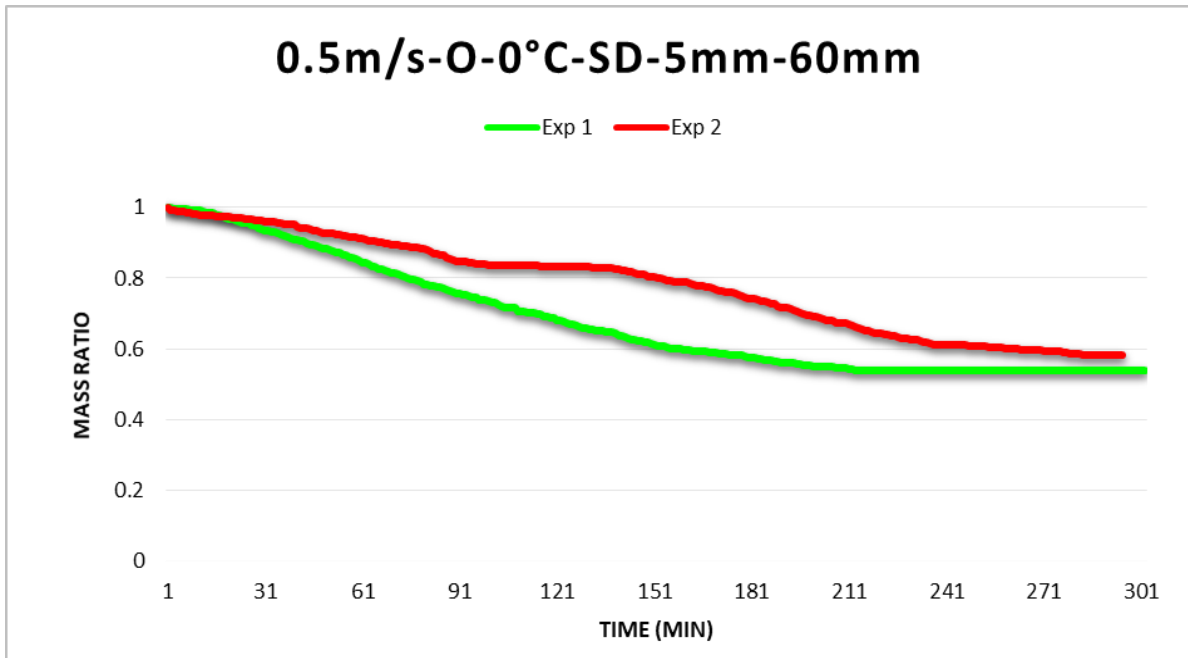
Figure D1. 8: Solar drying overcast conditions
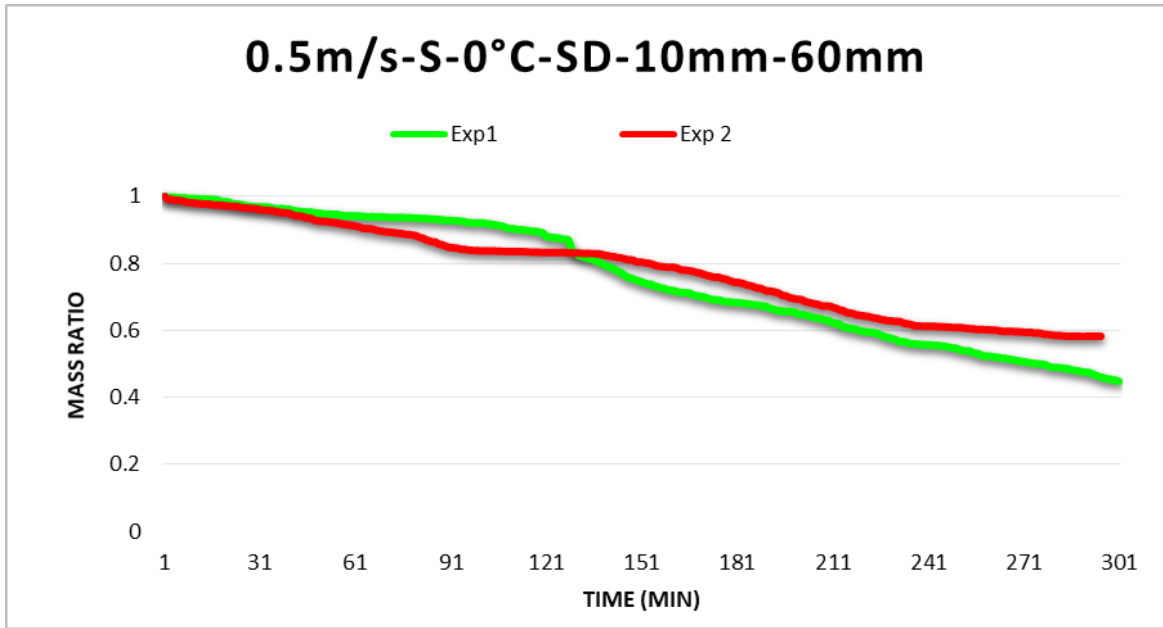
Figure D1. 9: Solar drying 10 mm thickness
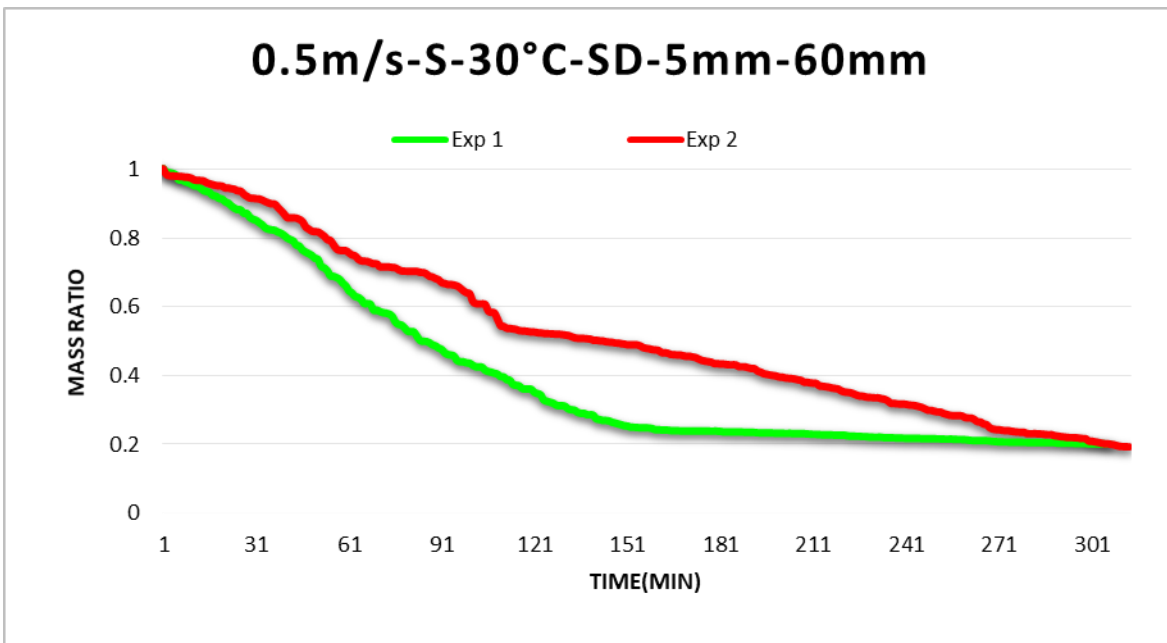
Figure D1. 10: Solar drying 30 ºC air preheating
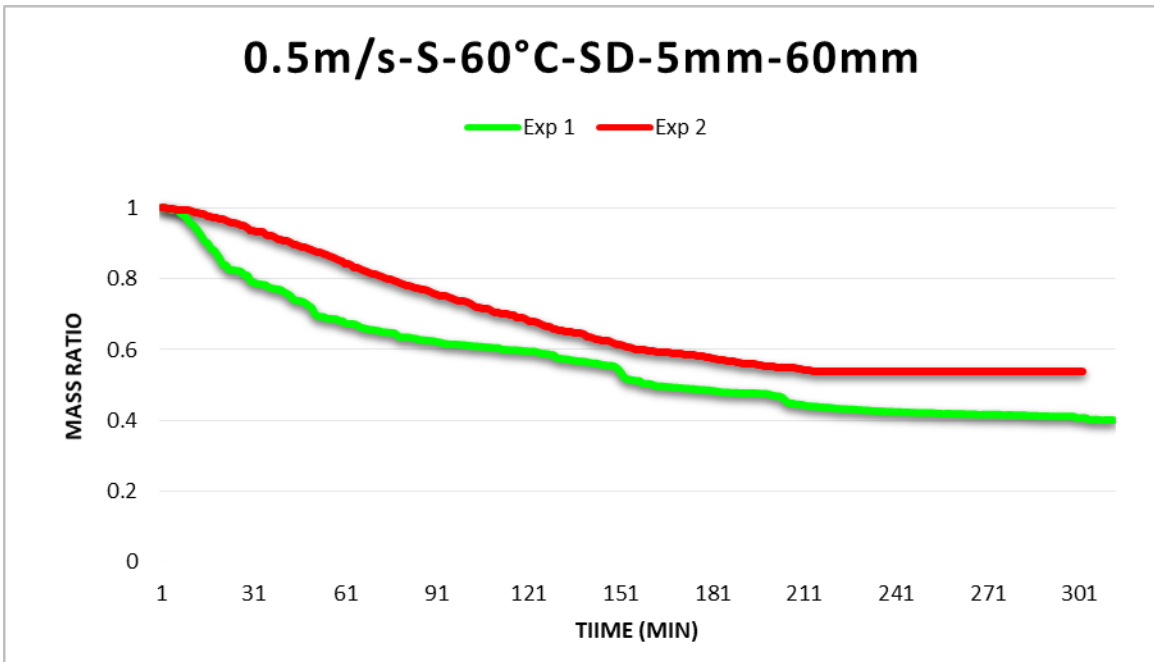
Figure D1. 11: Solar drying 60 ⁰C air preheating
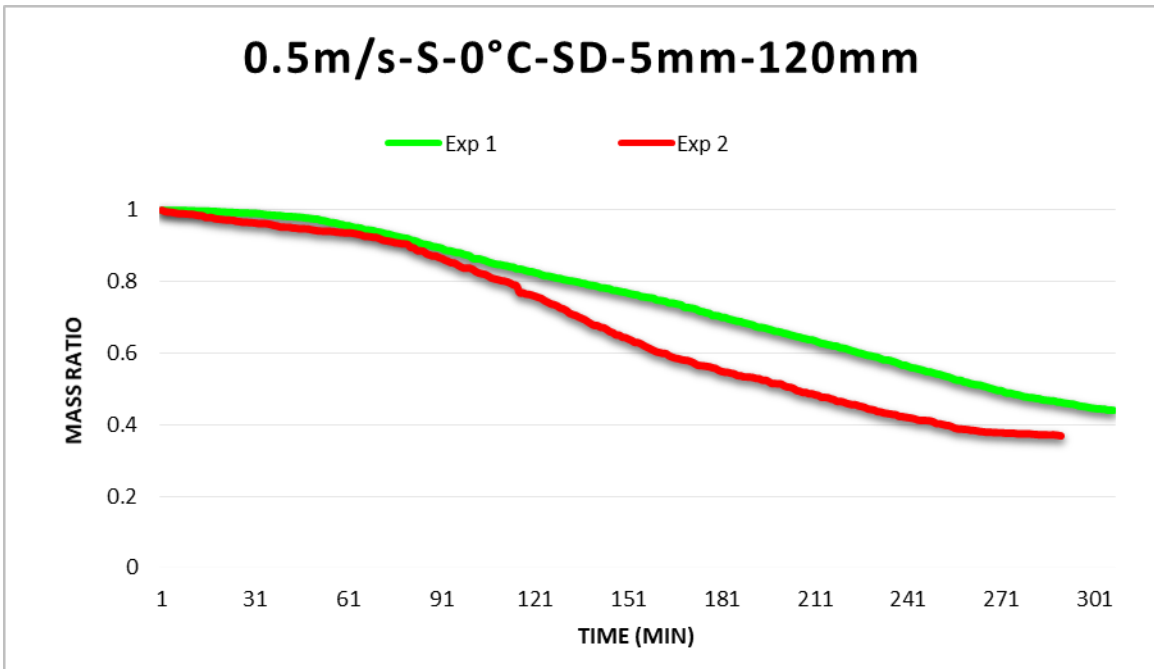
Figure D1. 12: Solar drying 120 mm surface diameter
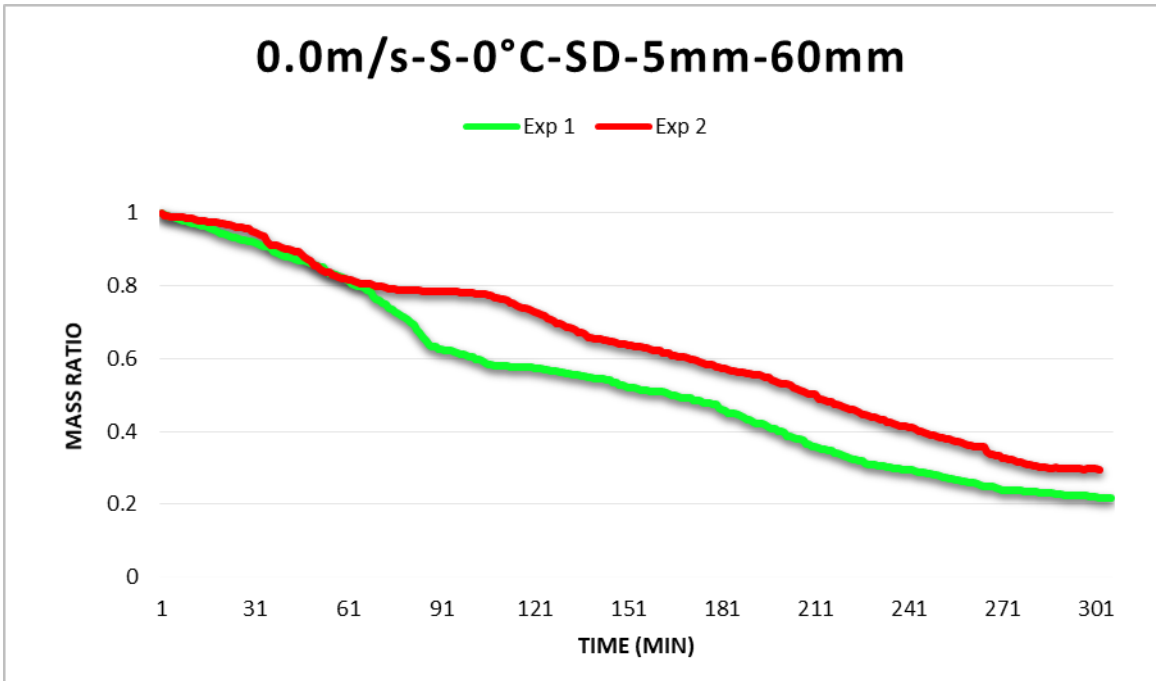
Figure D1. 13: Solar drying natural convection
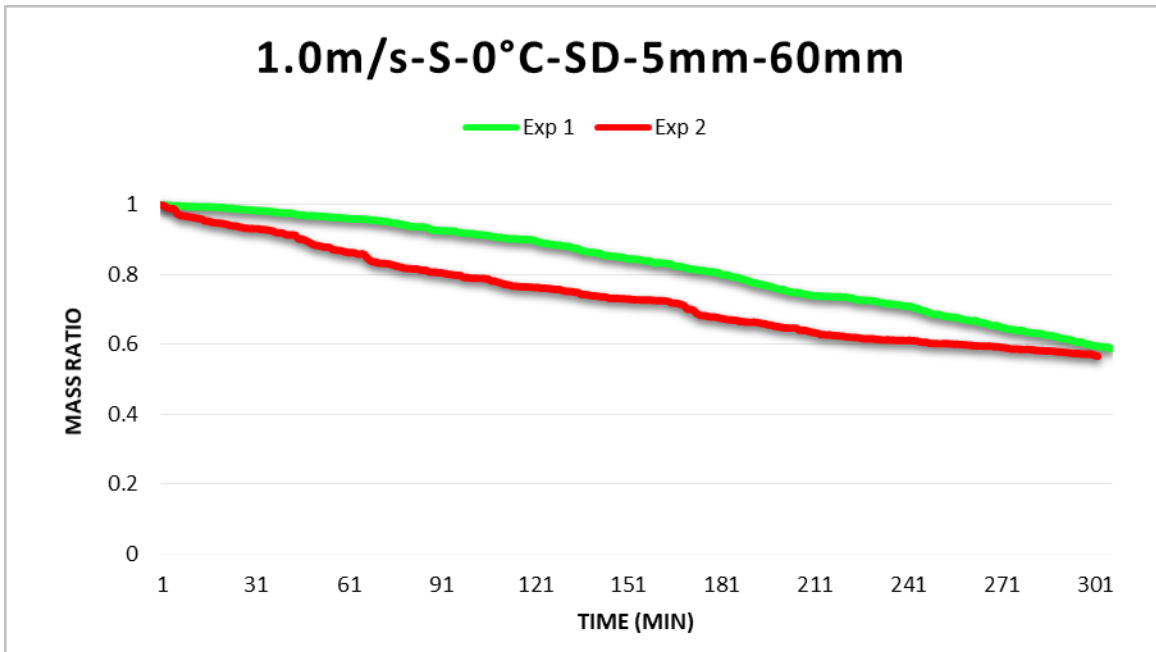
Figure D1. 14: Solar drying 1.0 m/s air flow velocity

D2: Solar irradiance graphs
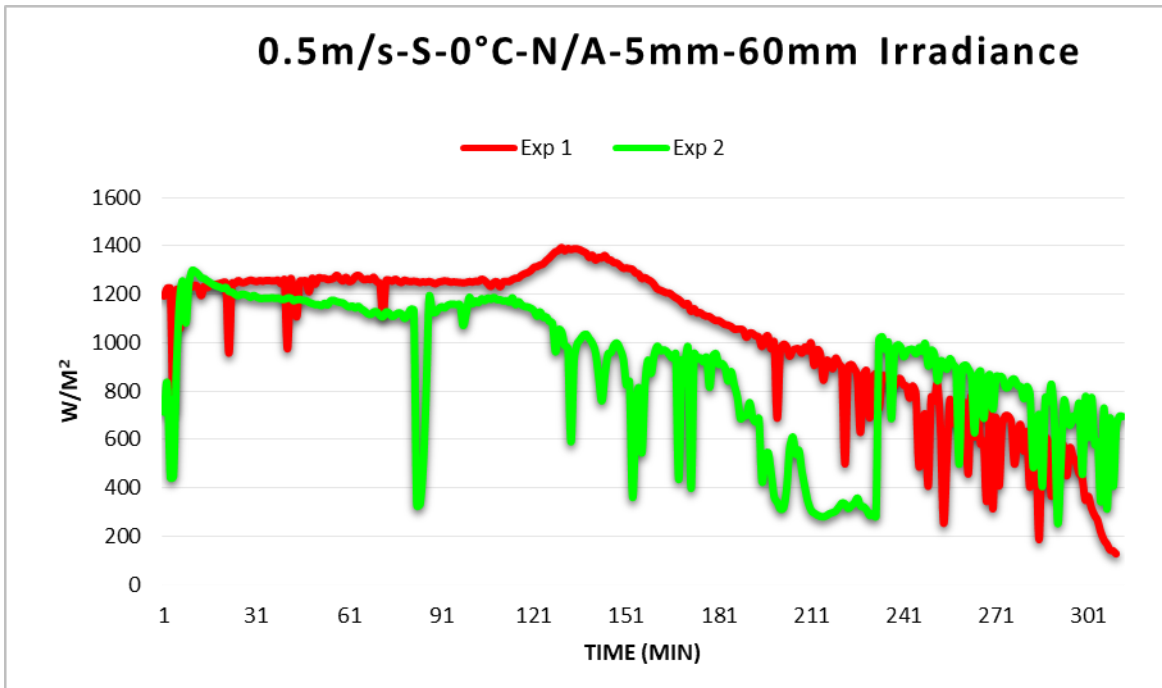
Figure D2. 1: Sunny conditions solar irradiance
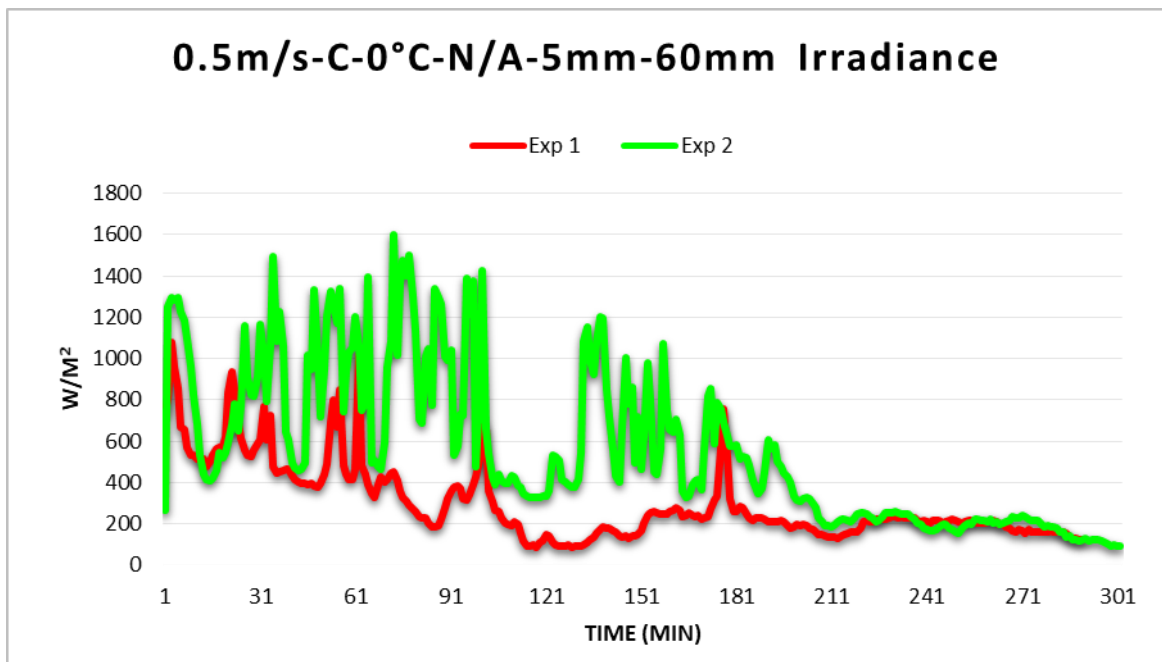
Figure D2. 2: Cloudy conditions solar irradiance
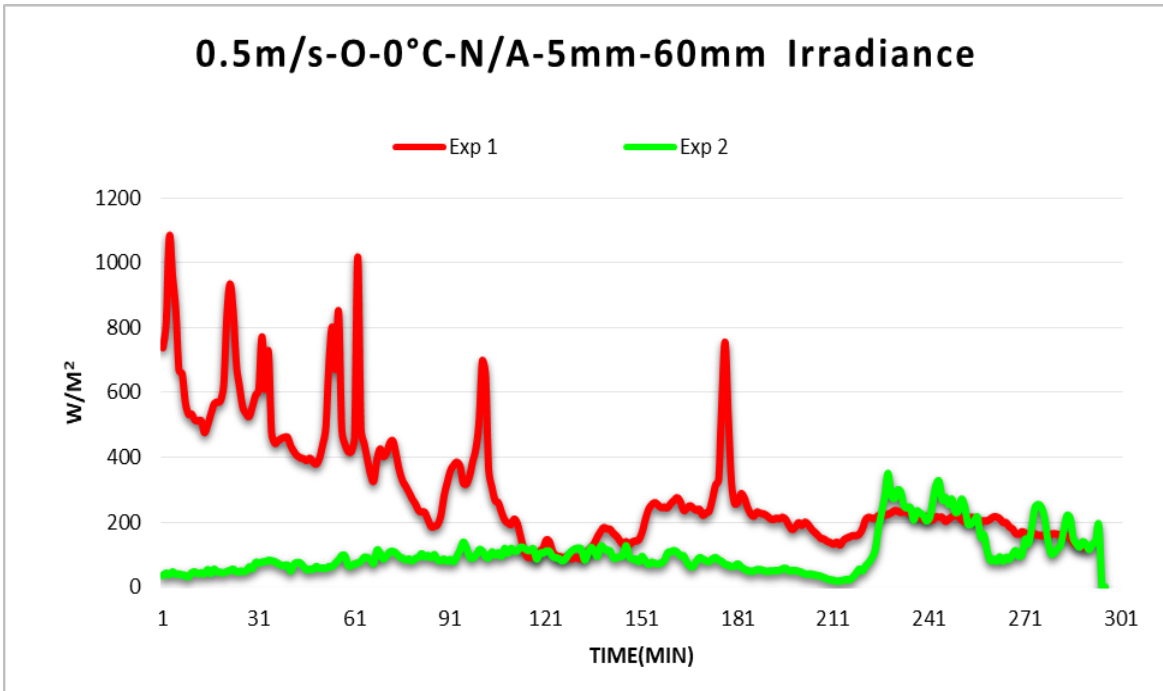
Figure D2. 3: Overcast conditions solar irradiance
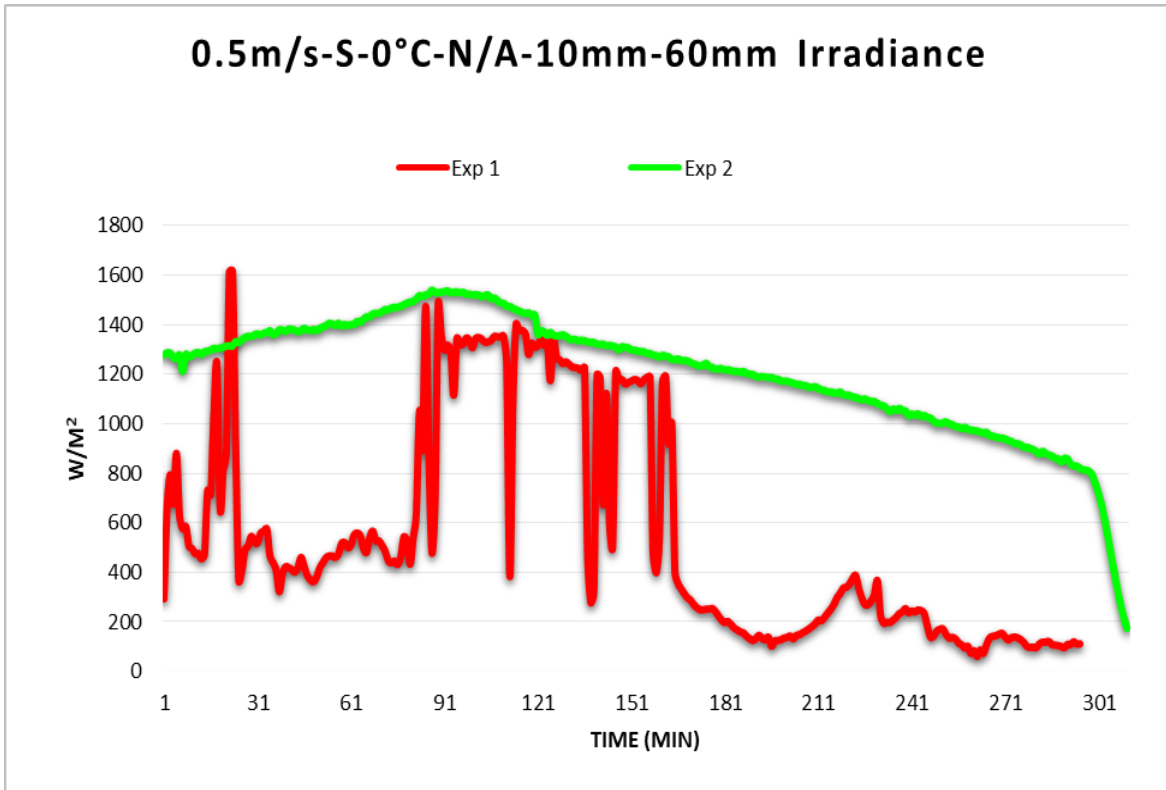
Figure D2. 4: 10 mm thickness solar irradiance
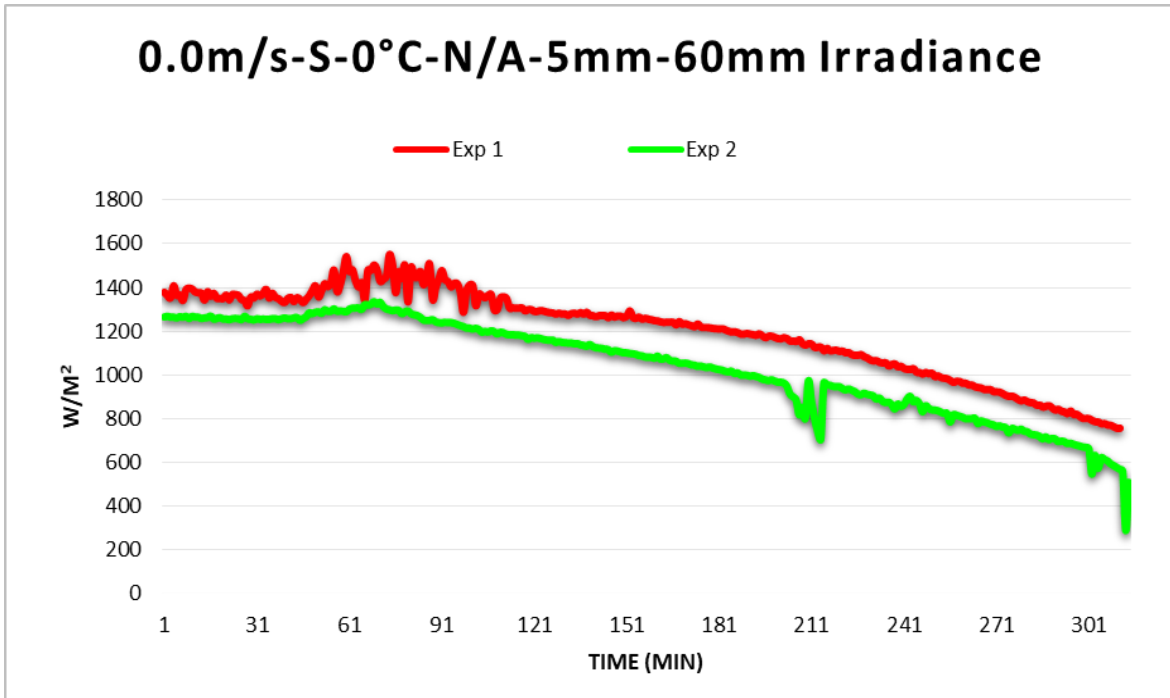
Figure D2. 5: Natural convection solar irradiance
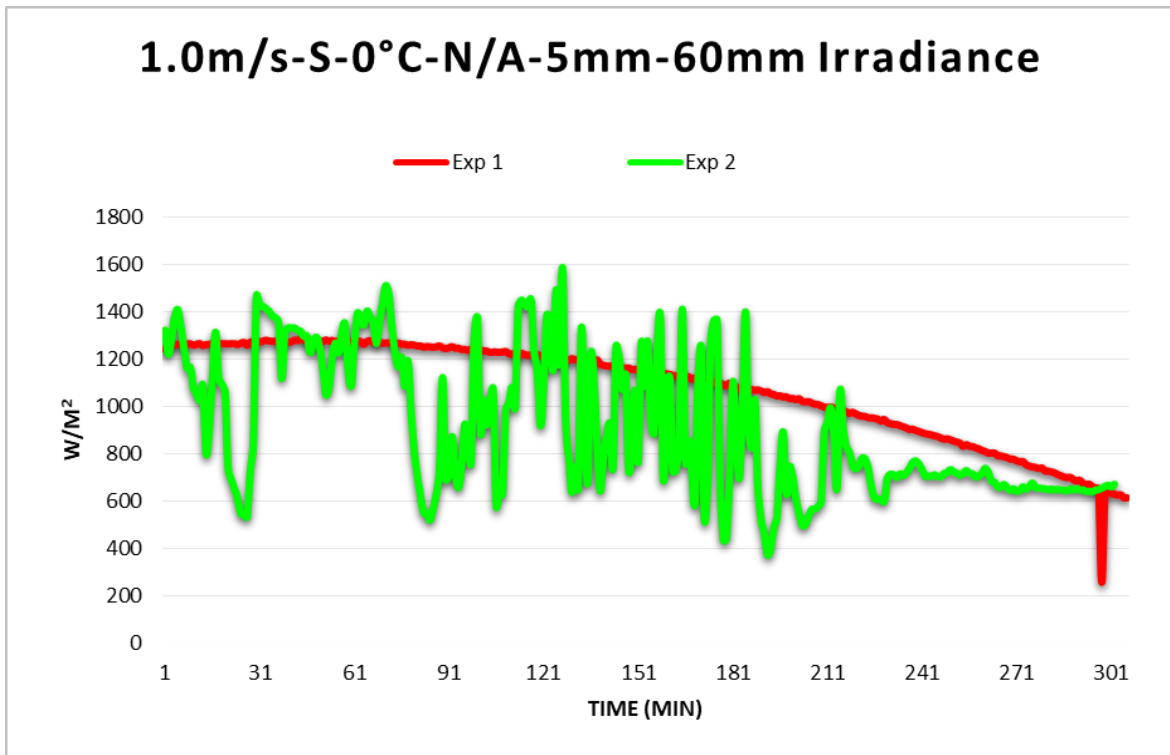
Figure D2. 6: 1.0 m/s air flow velocity solar irradiance
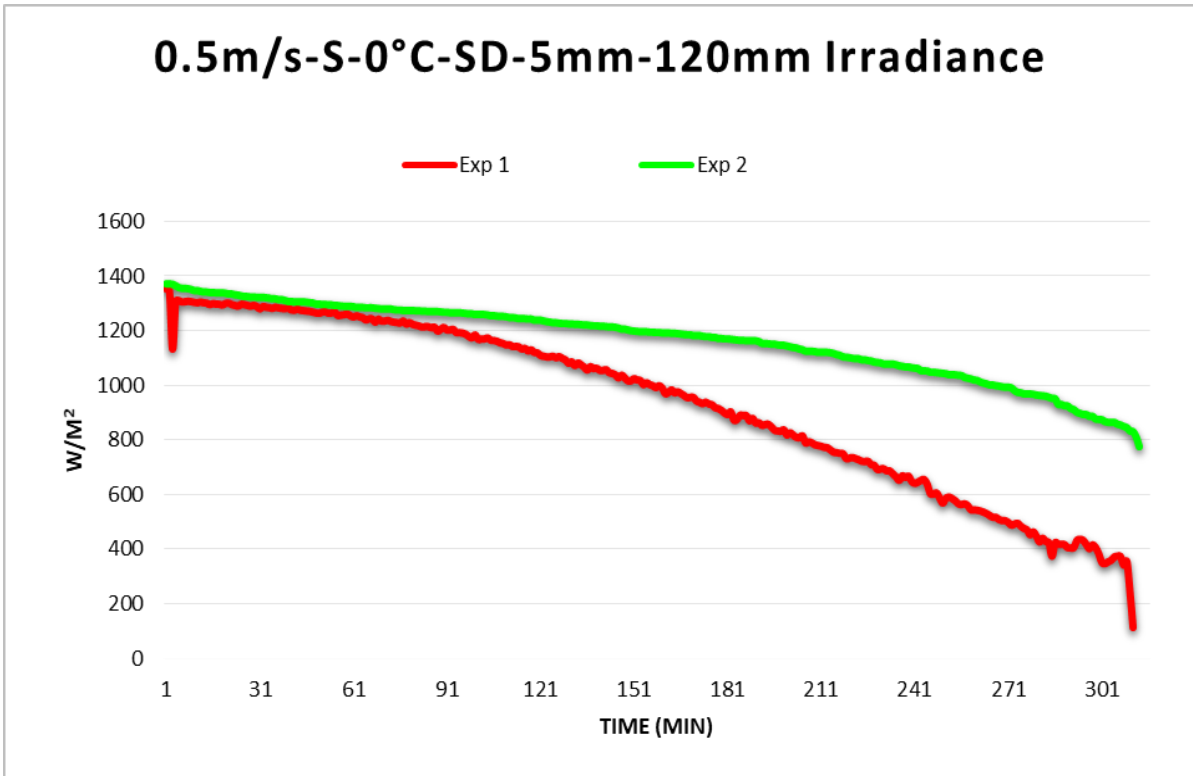
Figure D2. 7: 120 mm surface diameter solar irradiance
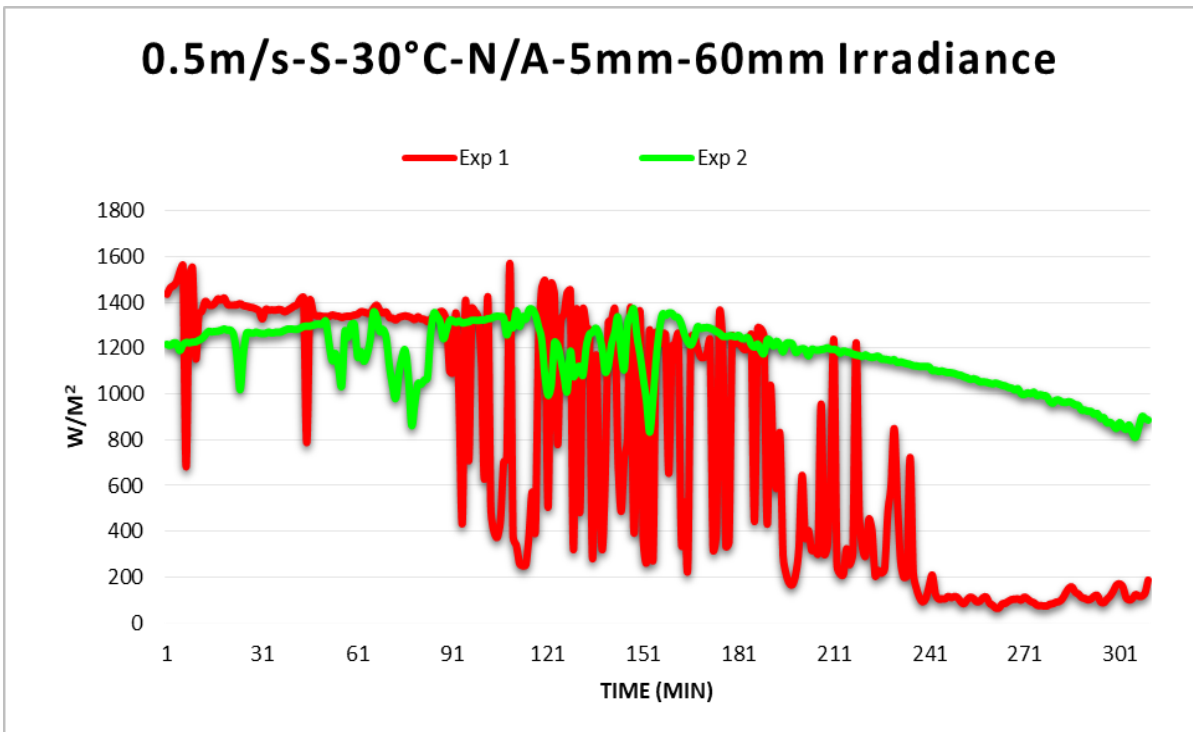
Figure D2. 8: 30 ºC air preheating solar irradiance
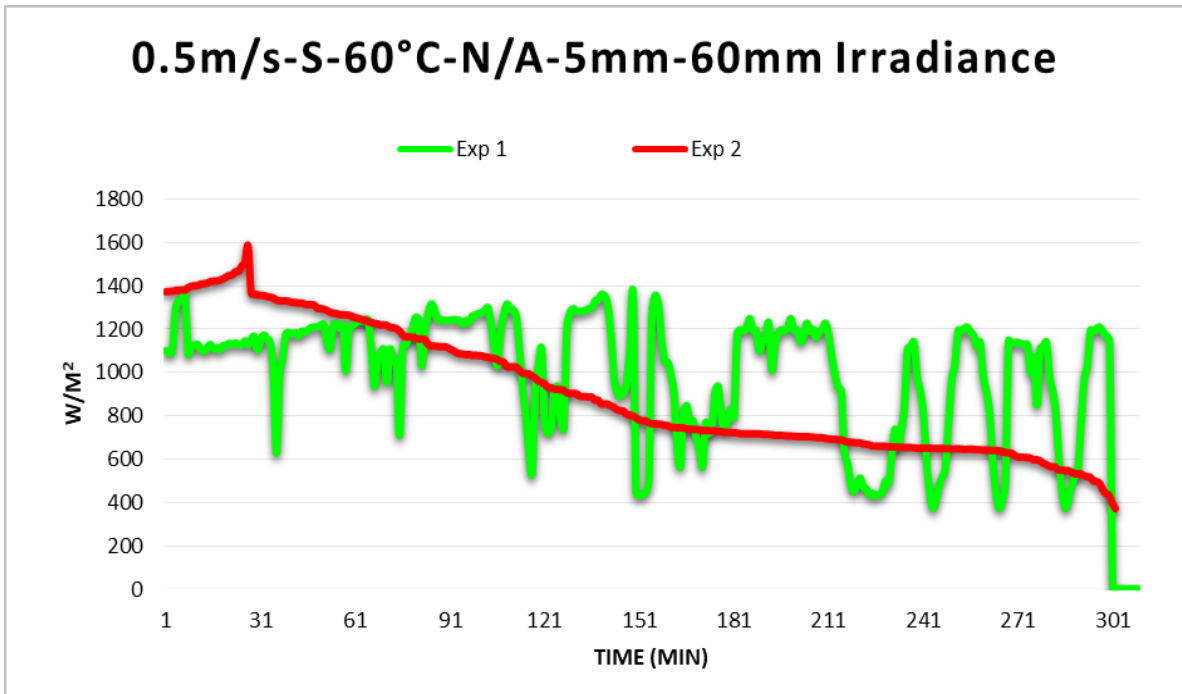
Figure D2. 9: 60 ºC air preheating solar irradiance

D3: Ambient and drying chamber temperature profiles
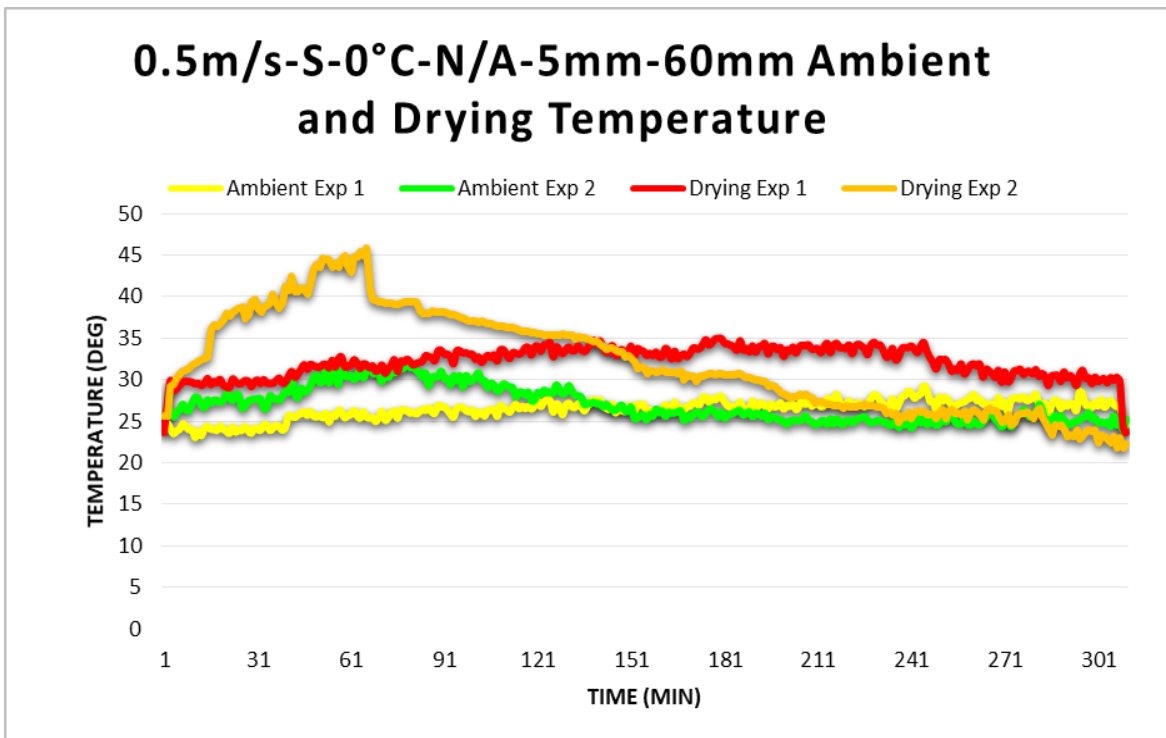
Figure D3. 1: Sunny conditions ambient and drying temperature
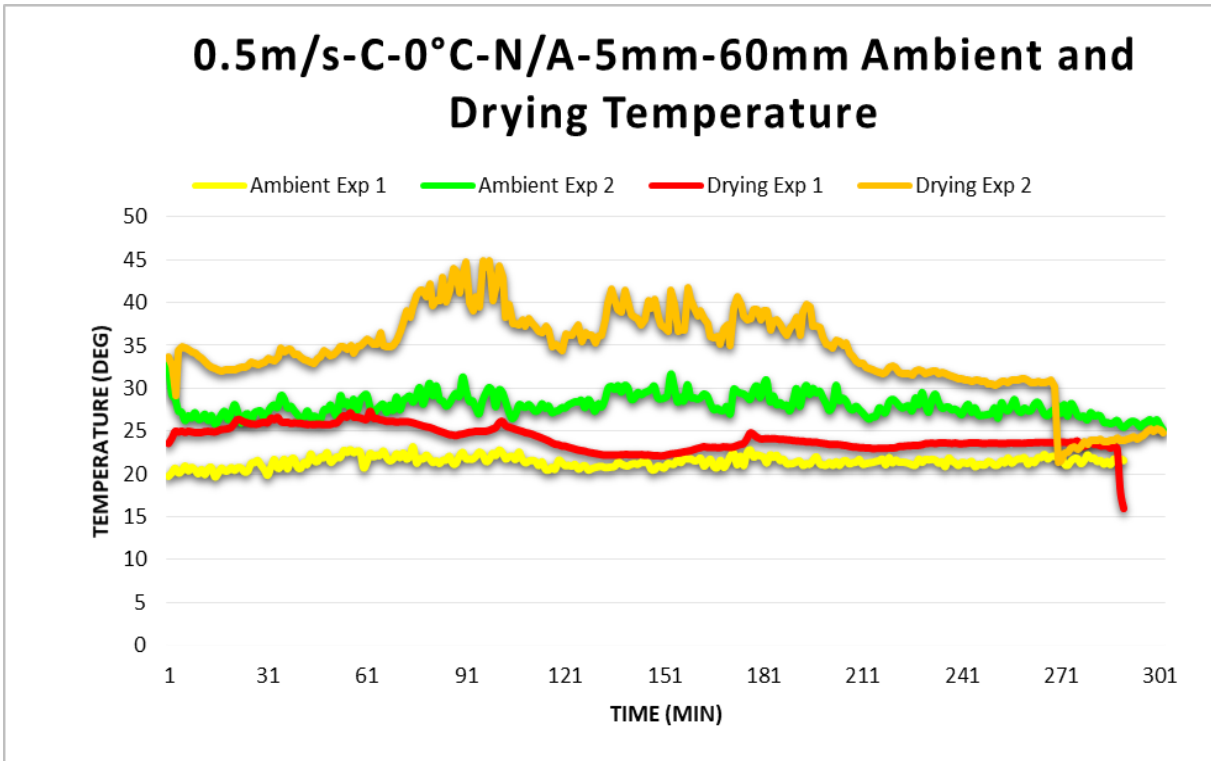
Figure D3. 2: Cloudy conditions ambient and drying temperature
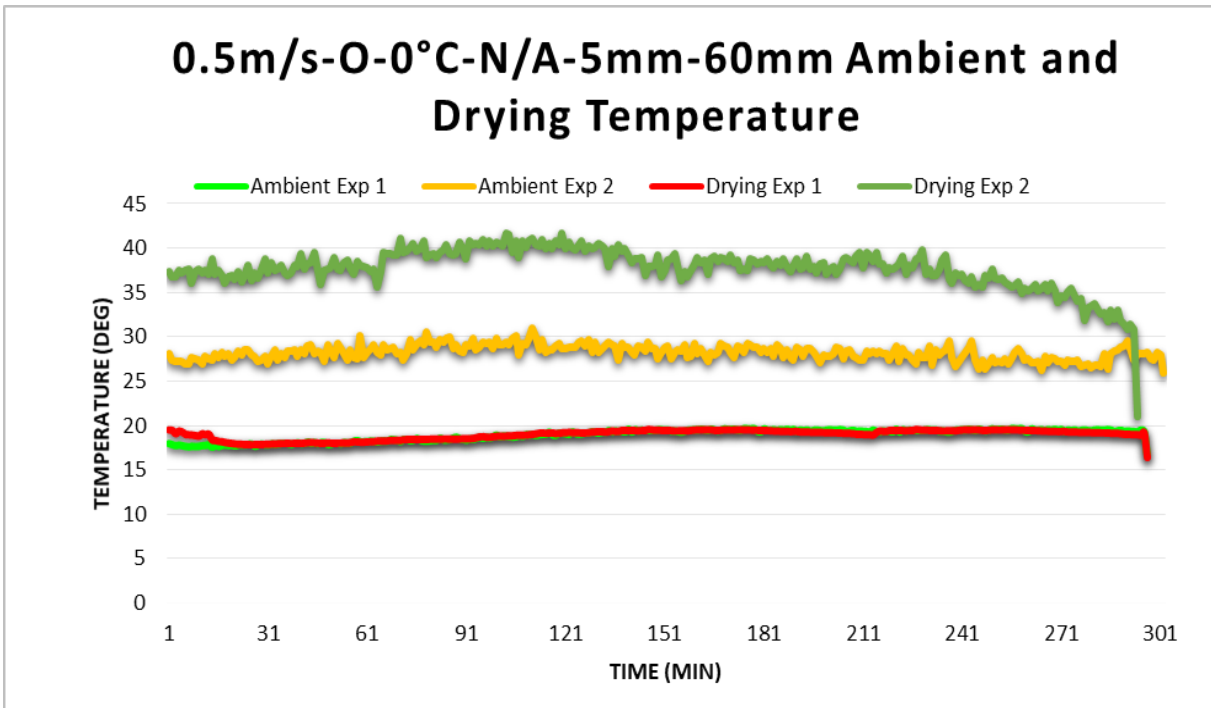
Figure D3. 3: Overcast conditions ambient and drying temperature
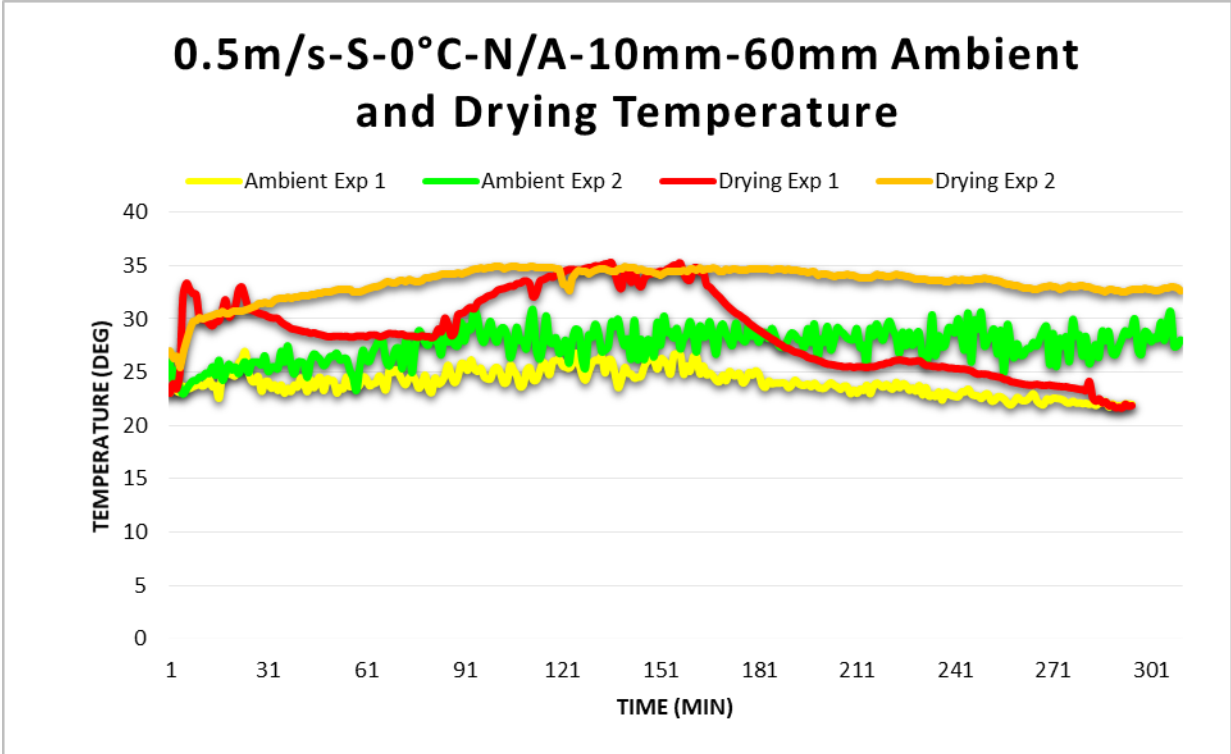
Figure D3. 4: 10 mm thickness ambient and drying temperature
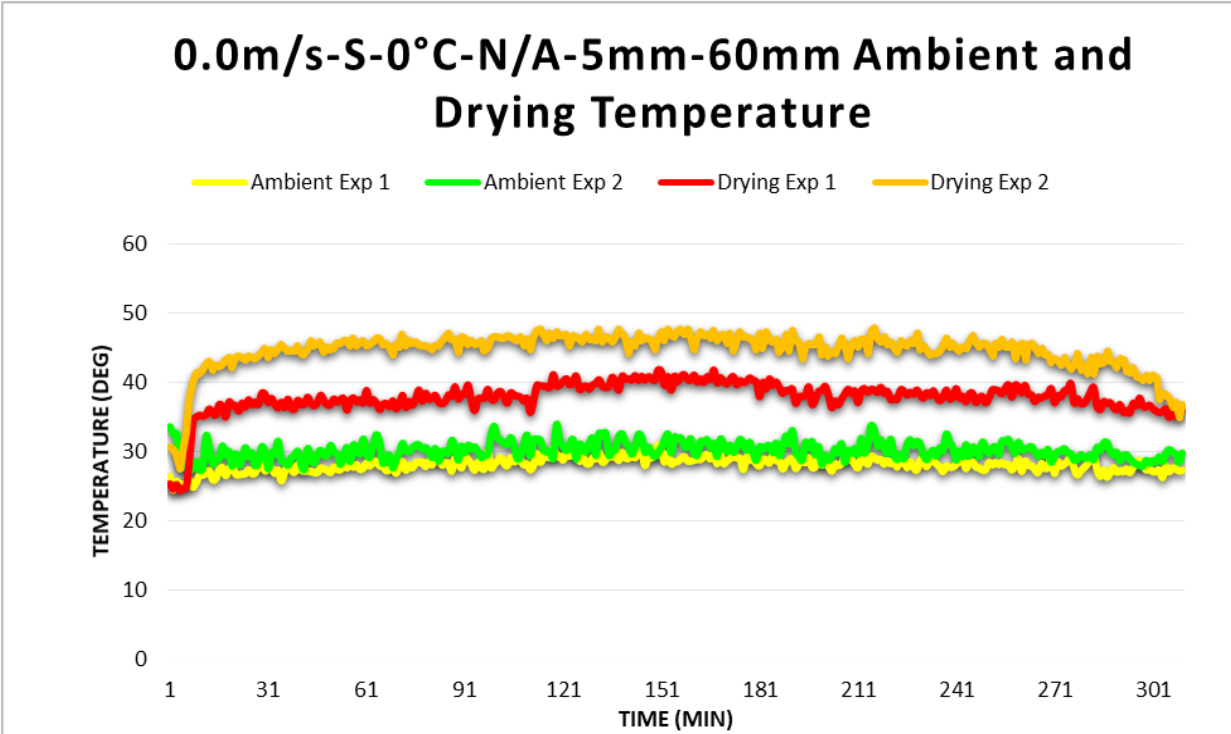
Figure D3. 5: Natural convection ambient and drying temperature
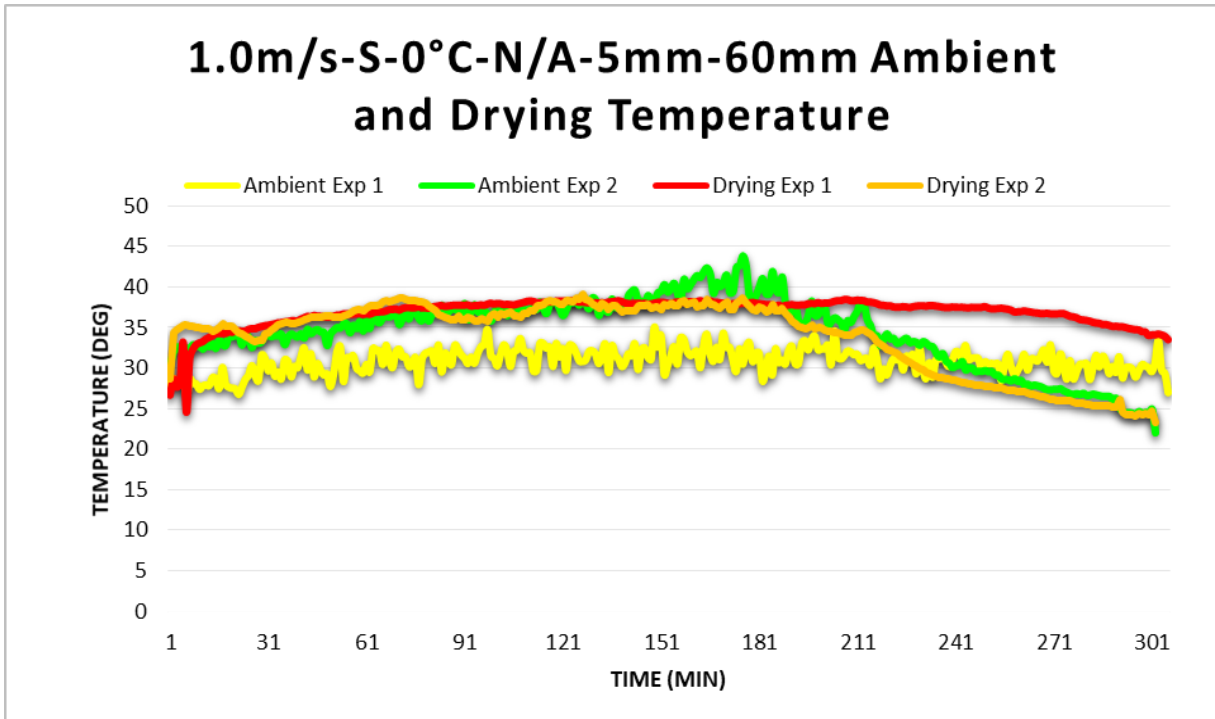
Figure D3. 6: 1 m/s airflow velocity ambient and drying temperature
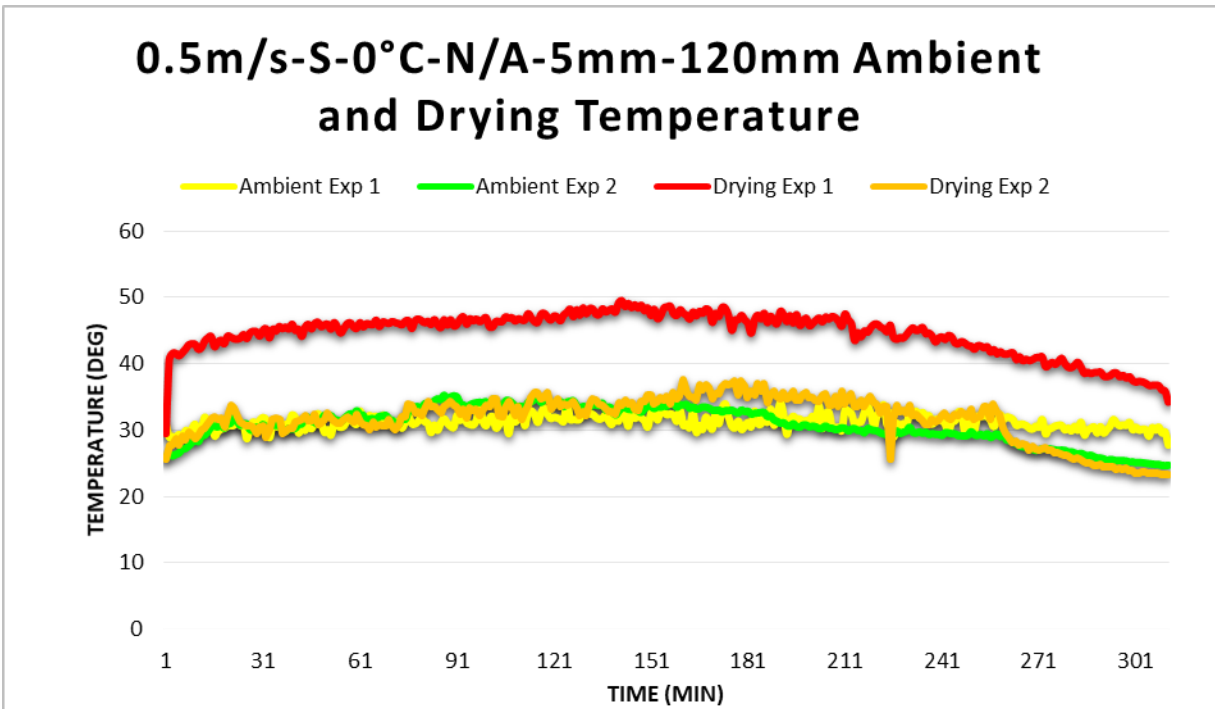
Figure D3. 7: 120 mm surface diameter ambient and drying temperature
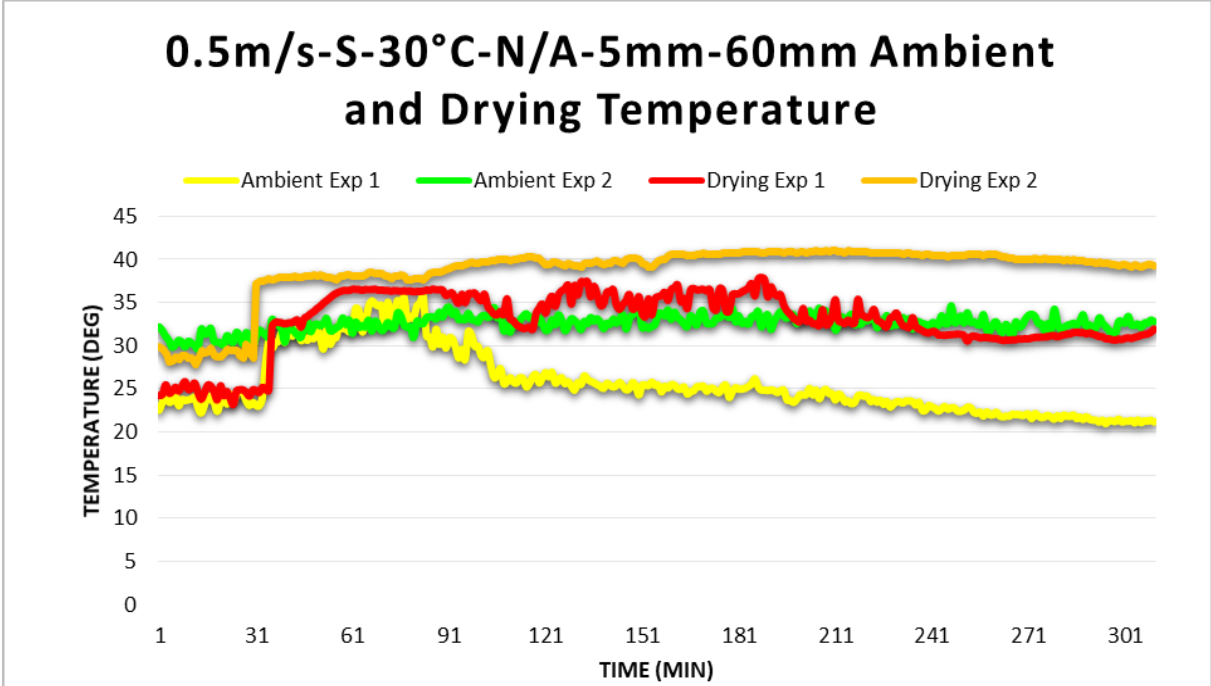
Figure D3. 8: 30 ºC air preheating ambient and drying temperature
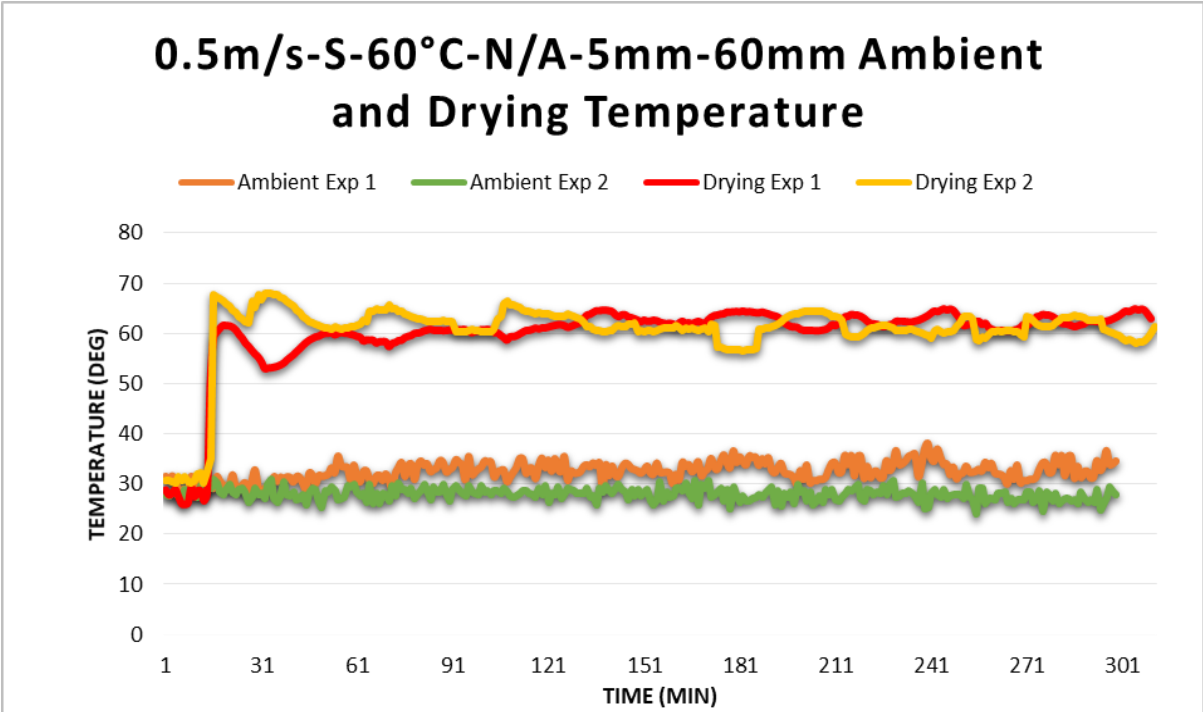
Figure D3. 8: 60 ºC air preheating ambient and drying temperature

B4: Core and surface temperature profiles
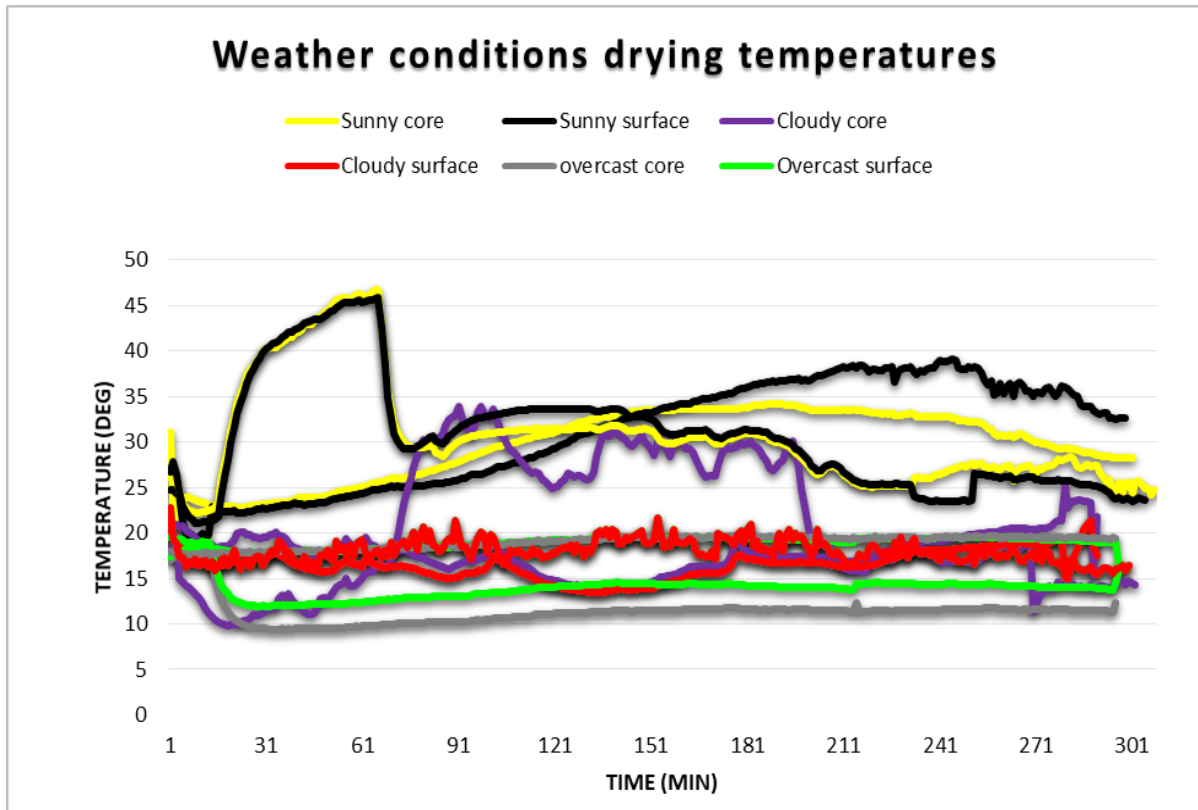
Figure D4. 1: Weather conditions core and surface temperature
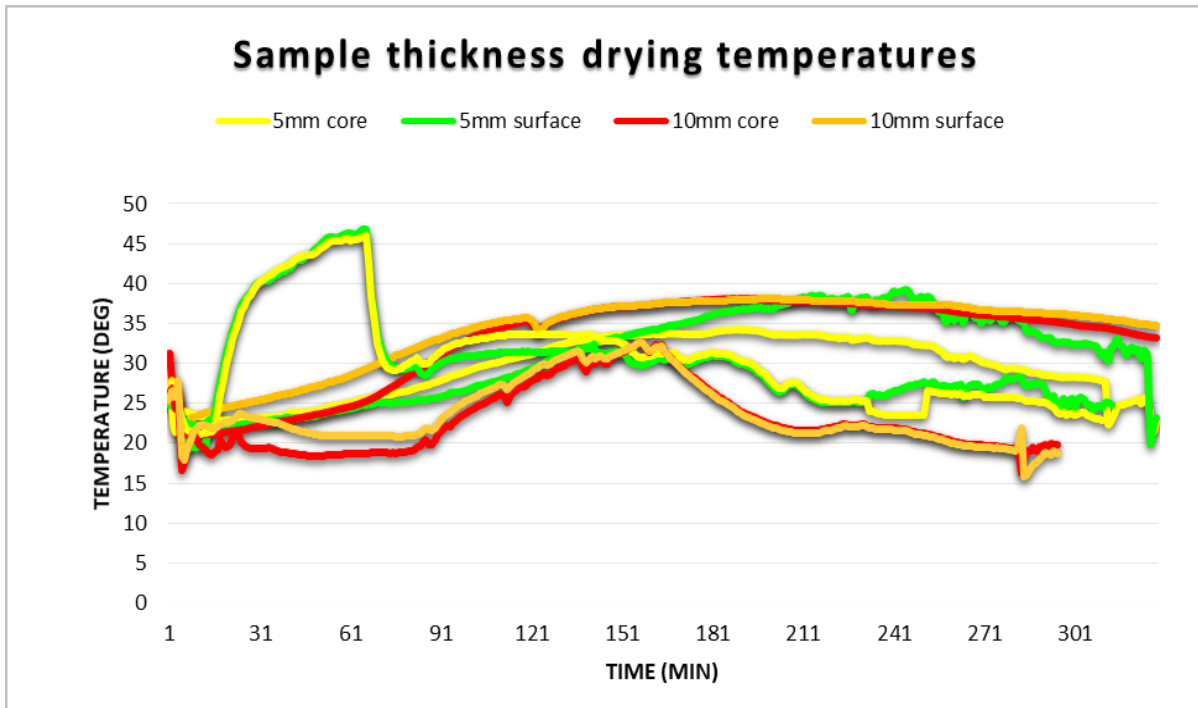
Figure D4. 2: Sample thickness core and surface temperature
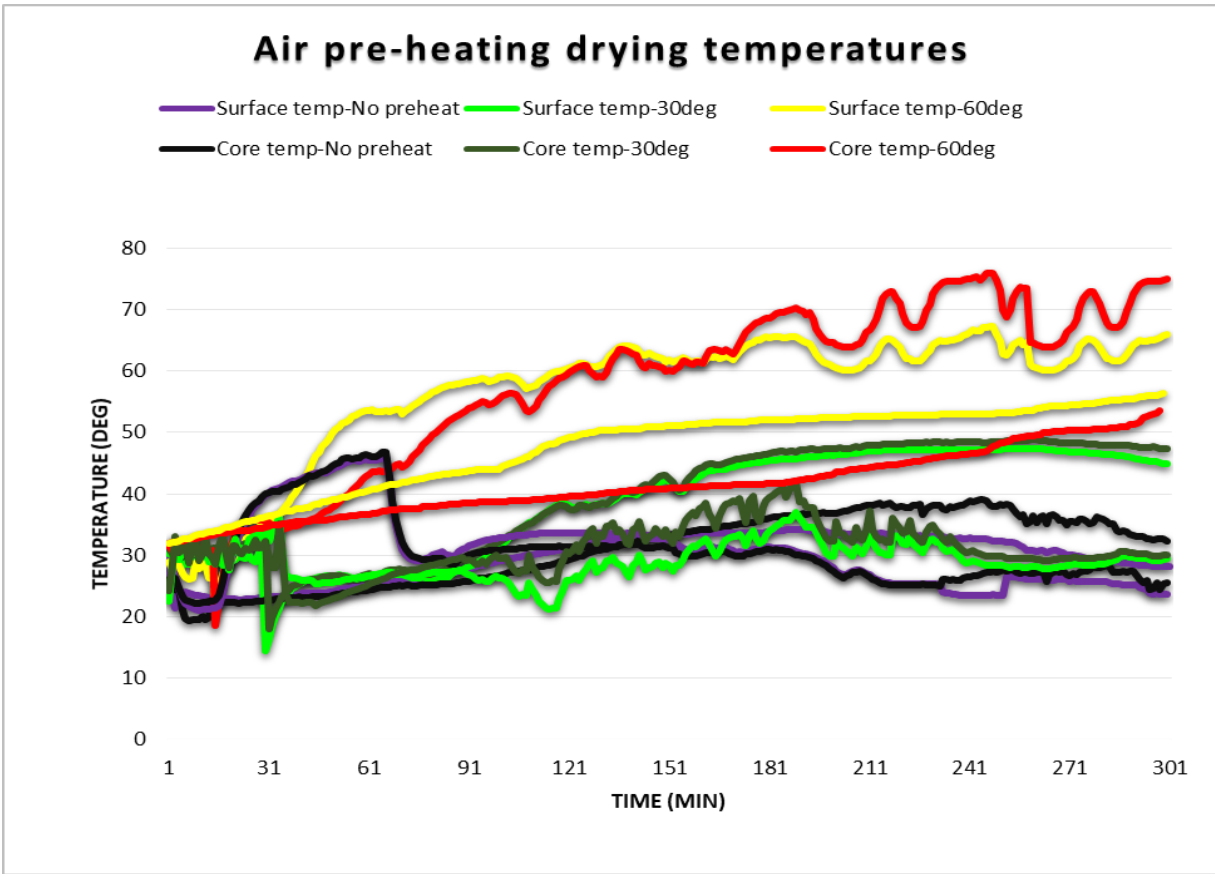
Figure D4. 3: Air preheating core and surface temperature
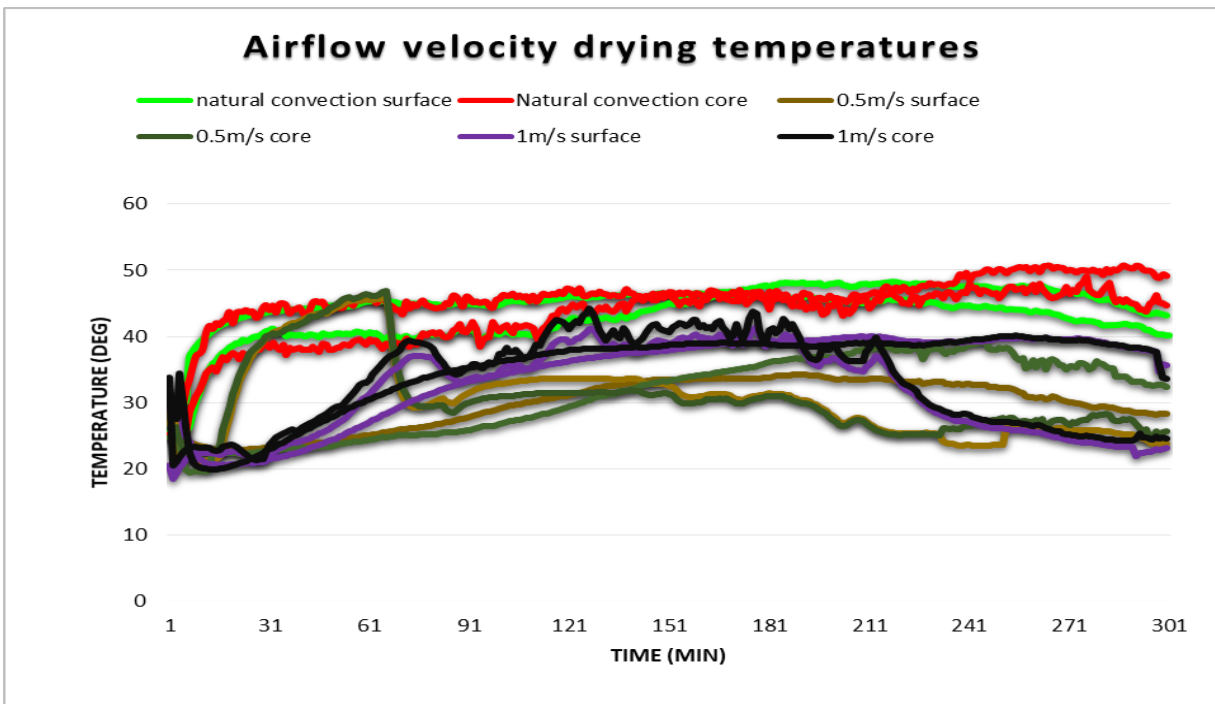
Figure D4. 4: Airflow velocity core and surface temperature
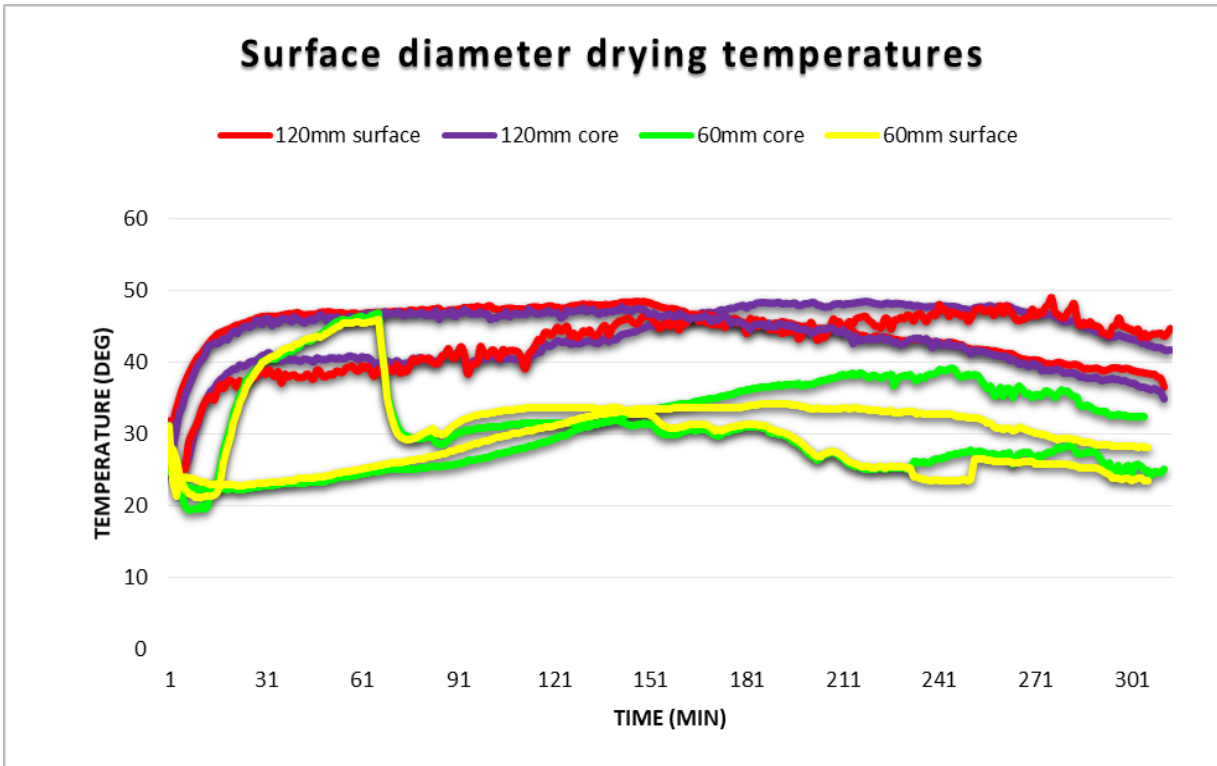
Figure D4. 5: Surface diameter core and surface temperature

D5: Humidity profiles
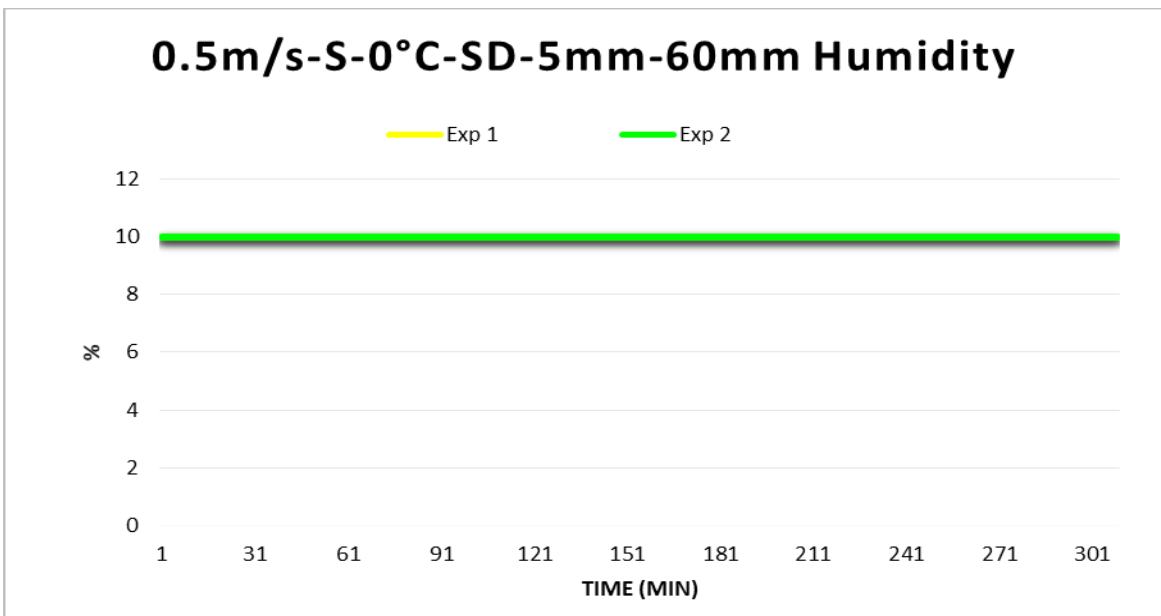
Figure D5. 1: Solar drying sunny conditions relative humidity
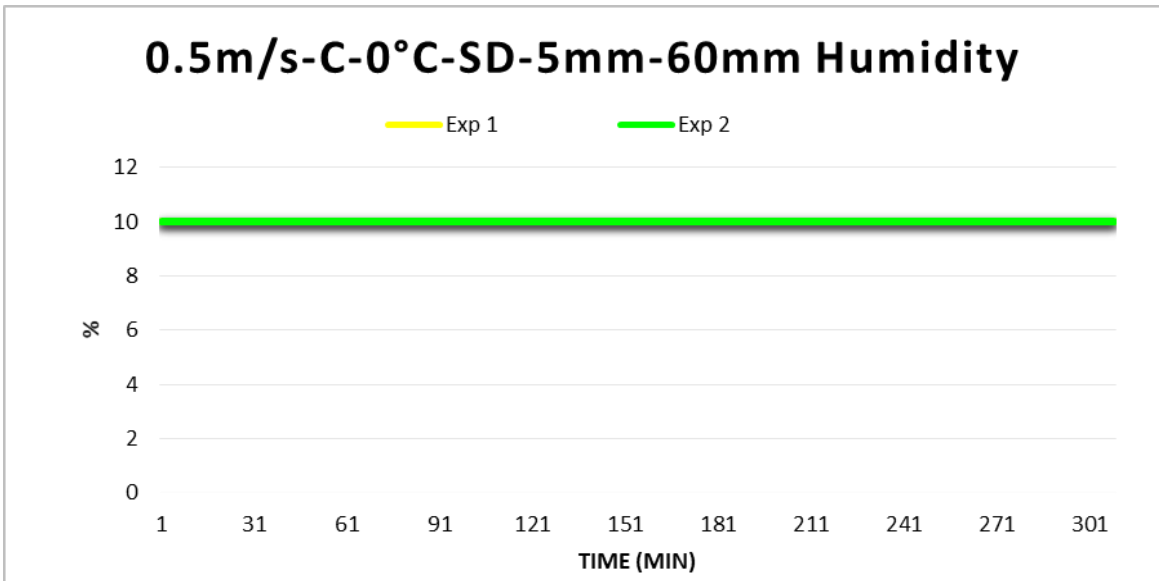
Figure D5. 2: Solar drying cloudy conditions relative humidity
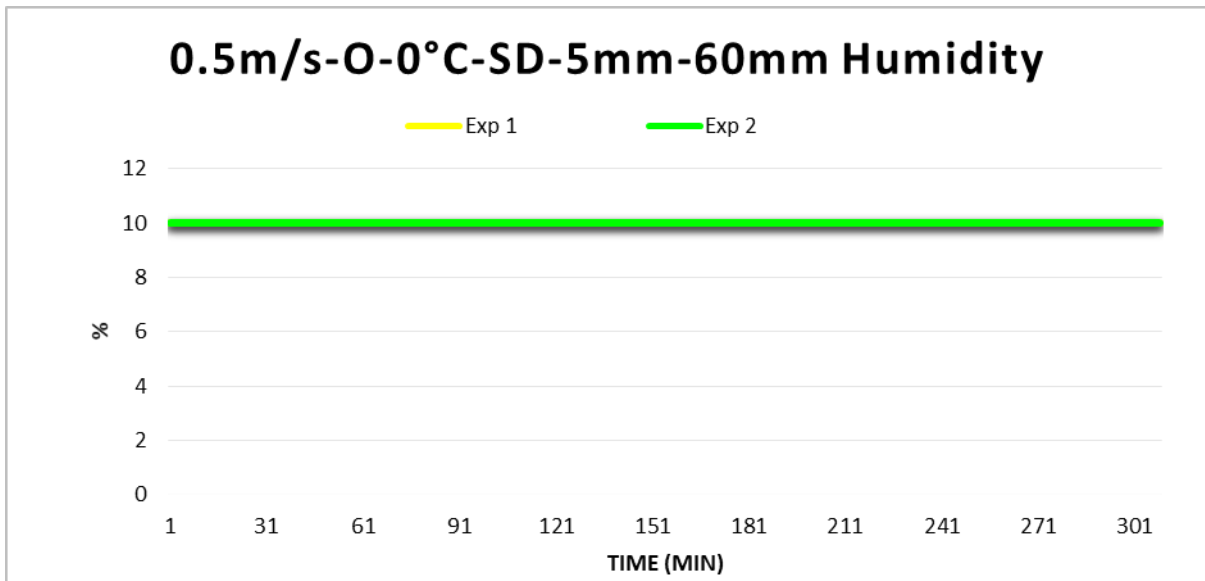
Figure D5. 3: Solar drying overcast conditions relative humidity
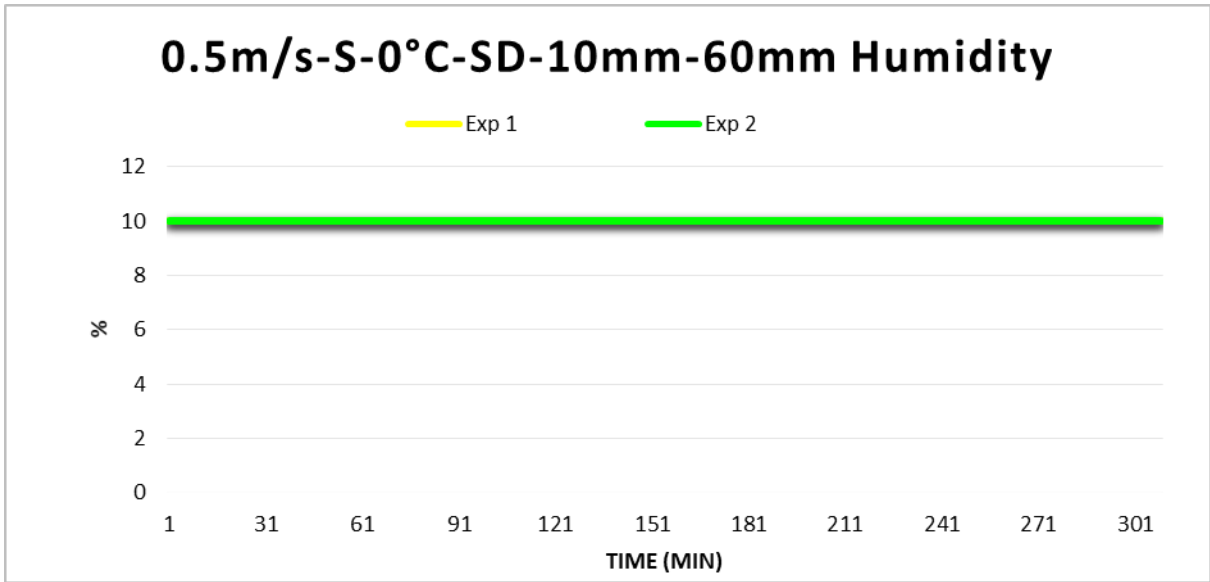
Figure D5. 4: Solar drying 10 mm sample thickness relative humidity
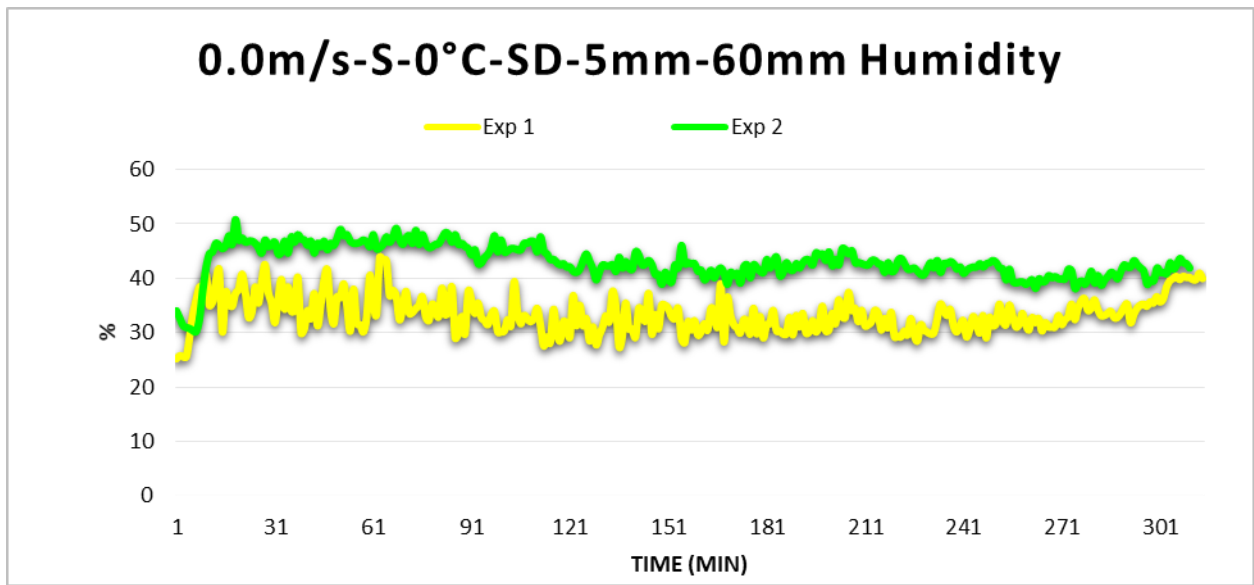
Figure D5. 5: Solar drying natural convection relative humidity
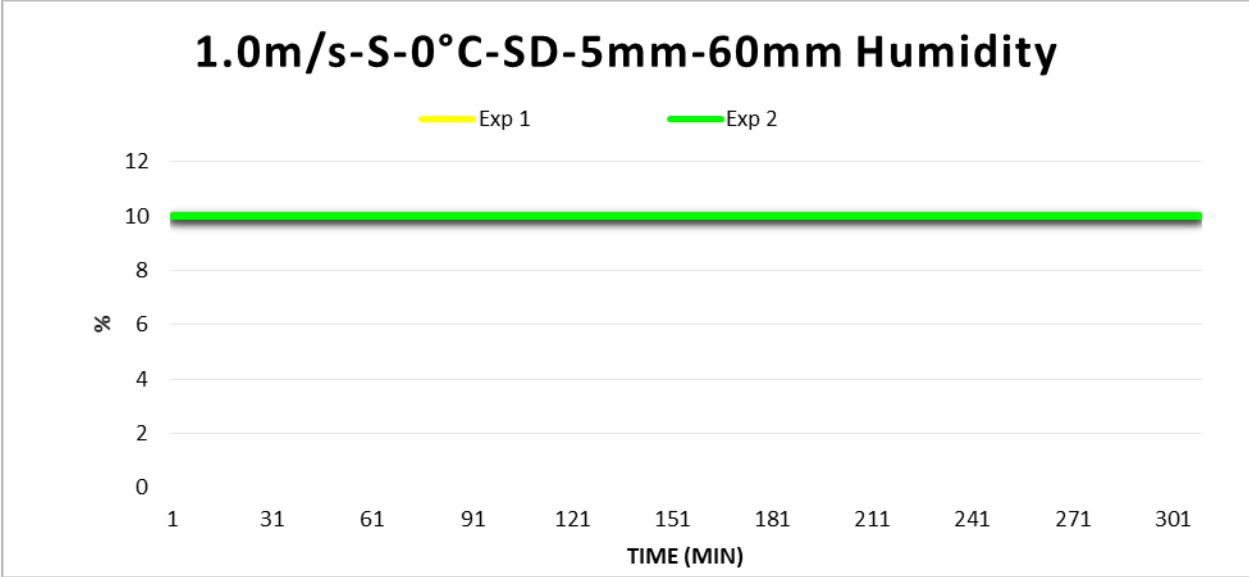
Figure D5. 6: Solar drying 1.0 m/s air flow velocity relative humidity
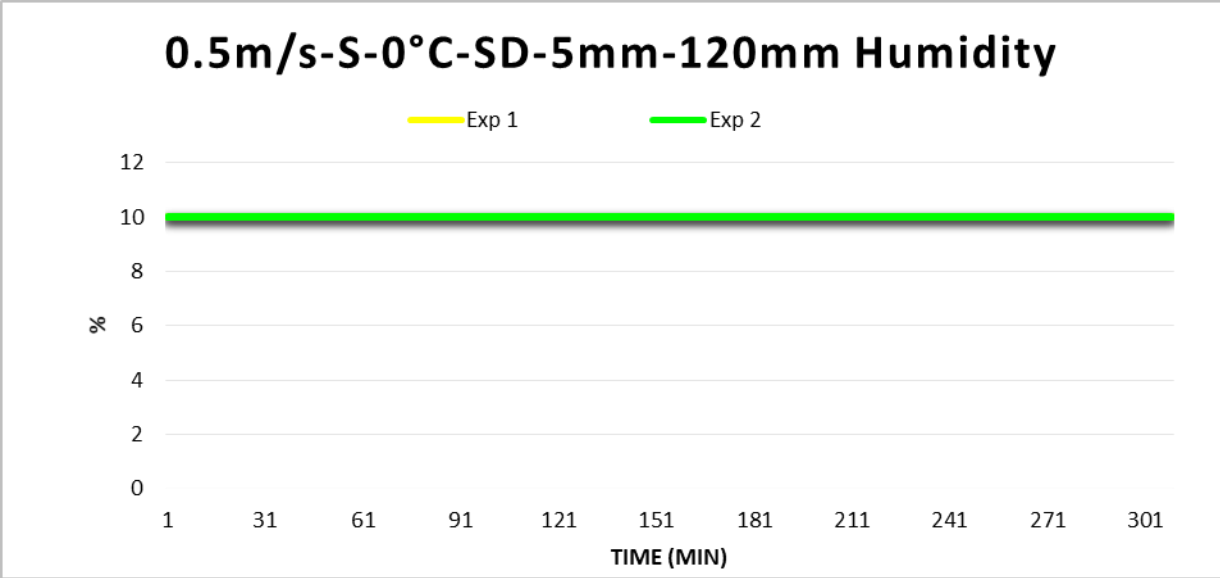
Figure D5. 7: Solar drying 120 mm surface diameter relative humidity
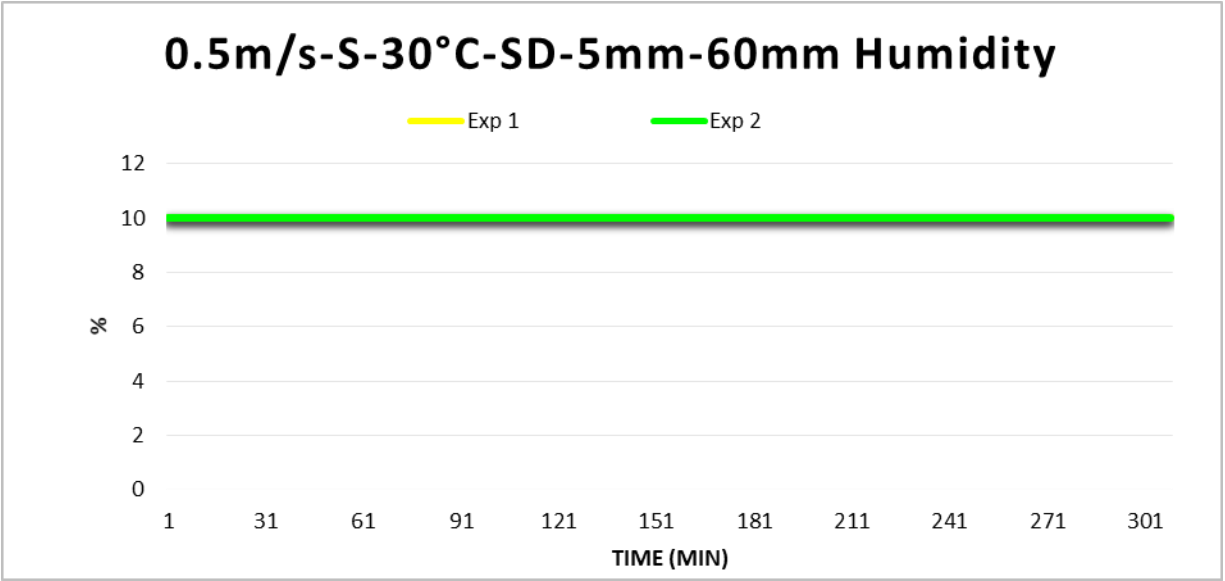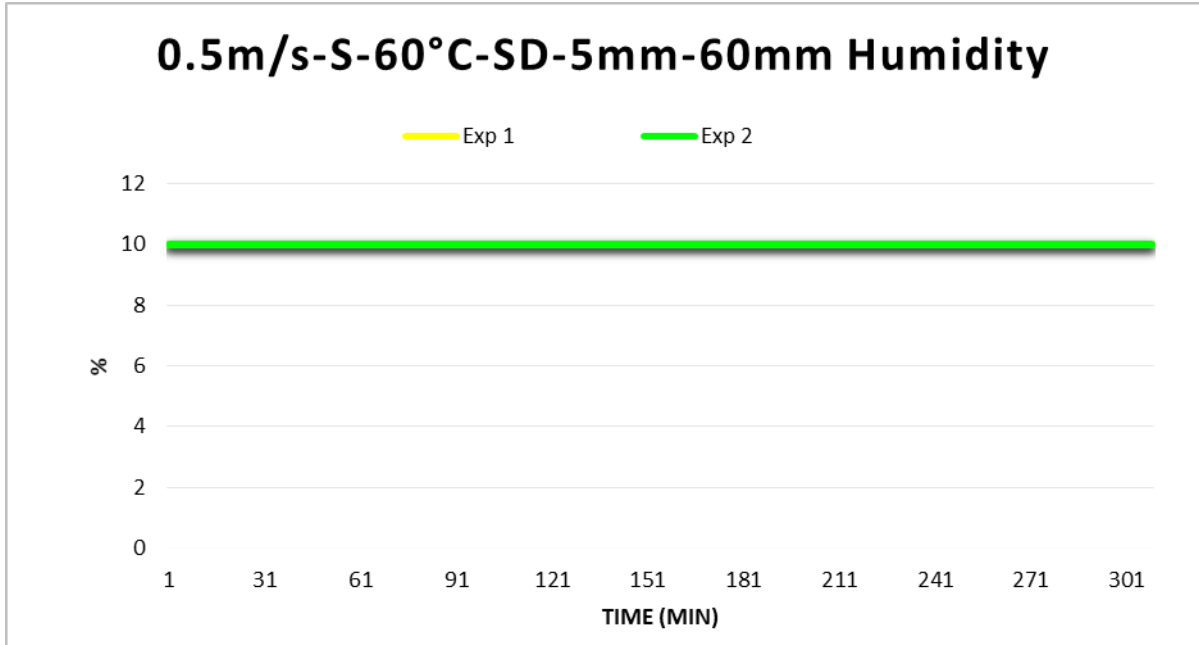
Figure D5. 8: Solar drying 30 ⁰C air preheating relative humidity

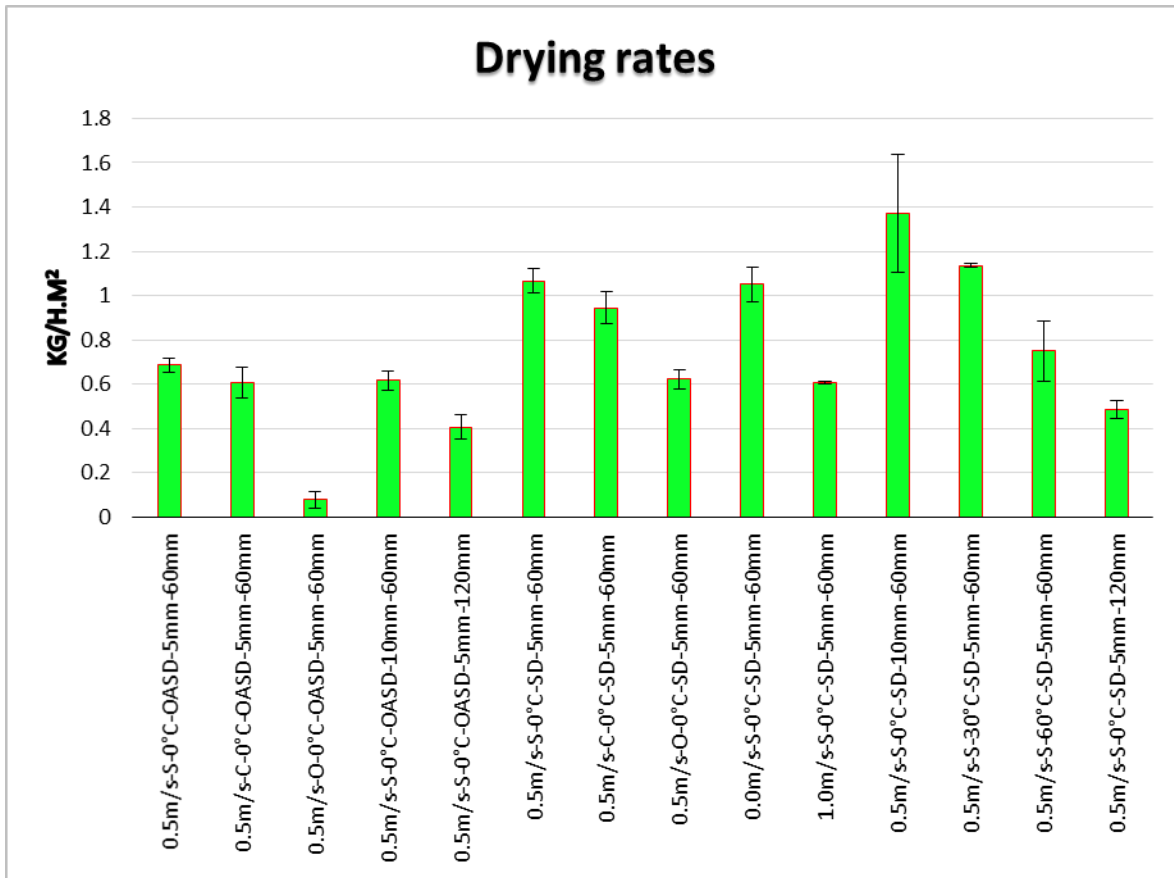**Figure D5. 9: Solar drying 60 ⁰C air preheating relative humidity**

D6: Drying rates

Figure D6. 1: Drying rates of samples under different test conditions of sample size, air properties and weather conditions

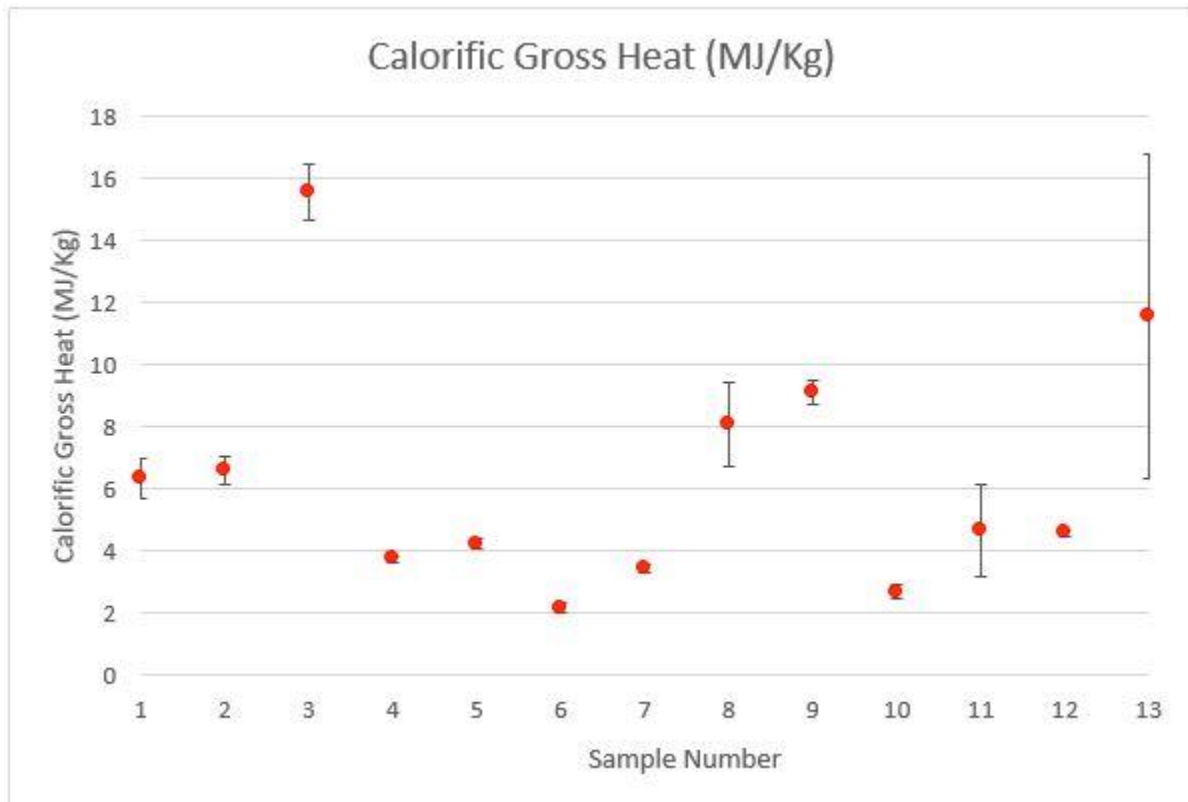## Appendix E: Calorific and nutrient analysis

E1: Calorific values

Figure E1. 1: Calorific values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying
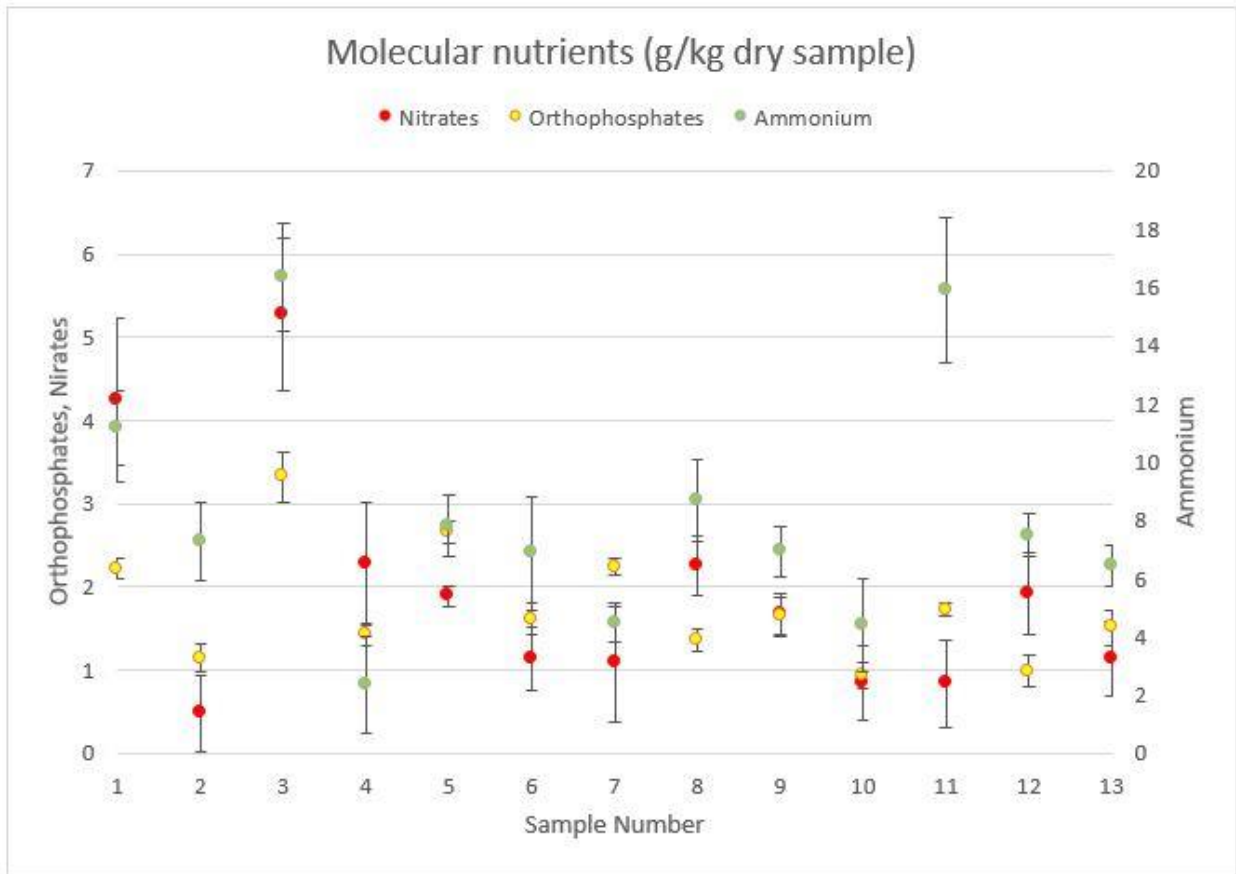
E2: Nutrient analysis

Figure E2. 1: Orthophosphates, nitrates and ammonium values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying
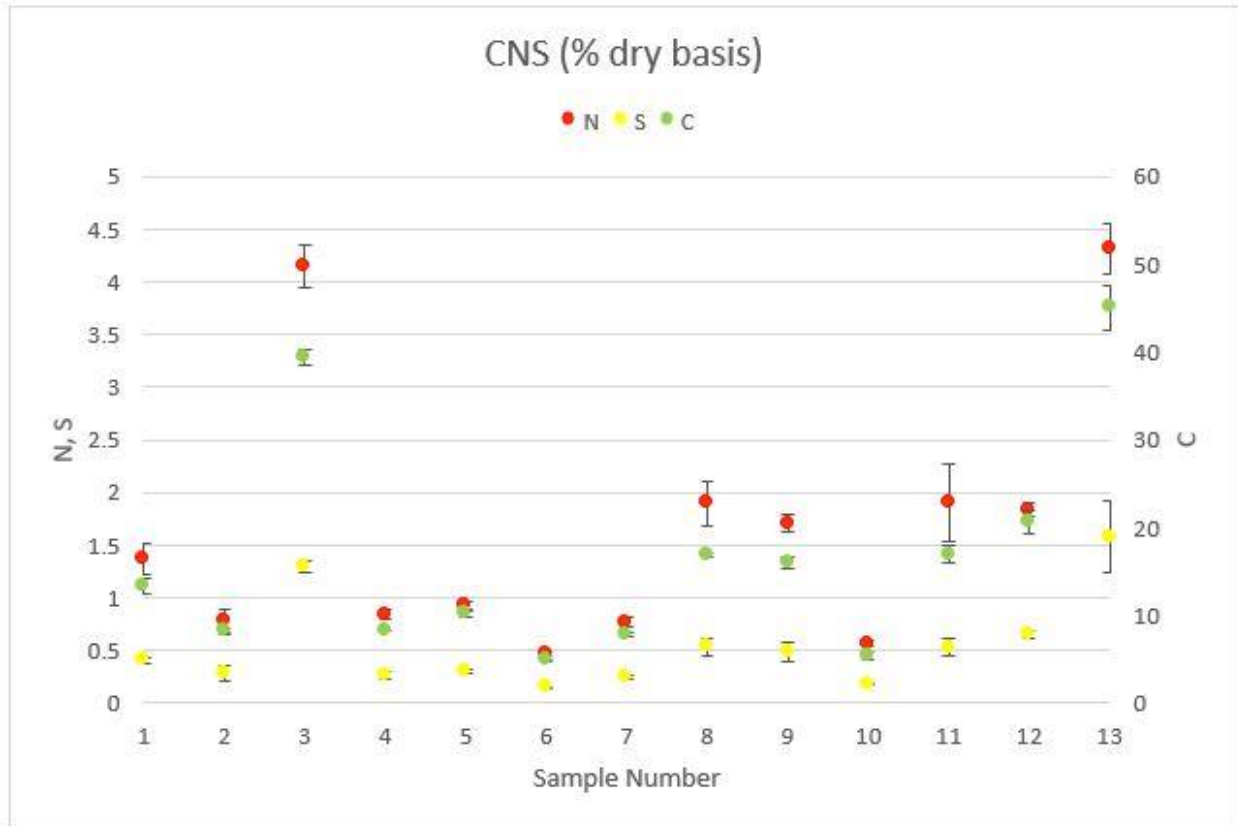
Figure E2. 2: Carbon, nitrogen and sulphur values of FS after solar and open air sun drying under varying drying conditions including wet FS prior to drying