

CRANFIELD UNIVERSITY

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Chemical Process Design of Solid Waste Management for Use in
Railway Rolling Stock

School of Water, Energy and Environment (SWEE)
Energy & Power

PhD Thesis
Academic Year: 2019 - 2022

Supervisor: Dr. Stuart Wagland
Associate Supervisor: Prof. Leon Williams
May 2022

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the degree of Doctor of Philosophy

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ABSTRACT

Proper management and disposal of highly wet hazardous sanitary solid wastes is of utmost importance for developing countries or parts of developed ones where sewage infrastructure is inaccessible. For instance, the sewage generated in on-board train toilets is being stored in a controlled emission tank (CET) fitted under the carriages that is further emptied in depot using extraction facilities. A method still requiring the final management of generated sludge while being costly with the train being pulled off the track.

Implementation of advanced thermal processes in small scales within the context of a decentralized wastewater treatment system has recently been found promising for the on-site stabilisation of sanitary faecal sludge. This research has outlined the requirements, challenges and constraints associated with the utilisation of thermal conversion technologies to aid in the development of system for this application. The thermochemical properties of multiple batches of solid wastes stored in CETs has been characterized for the first time to aid in the design of an innovative pyrolysis system. A drying unit for the simultaneous pre-treatment and resource recovery from faecal sludge is developed. The drying efficiency of the unit is evaluated, and the extent of nutrients recovered through the unit are discussed while design implications for further improvements are provided. Following this, the obtained data on the chemical properties of partially dried products are used for the testing and evaluation of a pyrolysis reactor.

The prototype was a novel twin auger pyrolysis reactor based on the application constraints and successfully commissioned. Effects of various process parameters on the conversion of faecal sludge is assessed through extensive chemical characterization of the process products (e.g., syngas, biooil and biochar). The outcomes of the research were discussed to provide insight into the by-products for further disposal or usage.

Throughout this thesis, points for further research are highlighted based on the findings and observations.

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LIST OF ABBREVIATIONS

AAD	Anaerobic Digestion
ATT	Advanced Thermal Treatment
AISI	American Iron and Steel Institute
BFB	Bubbling Fluidized Bed
CET	Controlled Emission Tank
COD	Chemical Oxygen Demand
CTC	Controlling Thermocouple
CFB	Circulating Fluidized bed
CV	Calorific Value
DAEM	Distributed Activation Energy Model
DTG	Differential Thermal Gravimetric
EVAC	Electrolux Environment Division
ER	Equivalence Ratio
EfW	Energy from Waste
FSM	Faecal Sludge Management
FBF	Fluidized Bed Furnace
FAHP	Fuzzy Analytic Hierarchy Process
FFR	Feedstock Flowrate
GHG	Greenhouse Gases
GC	Gas Chromatography
HHT	High eating Temperature
HHV	High Heating Value
HFS	Human Faecal Sludge
IXC	The InnovationXchange
IWPS	Integrated Waste Processing System
MHF	Multiple Hearth Furnace
MS	Mass Spectrometry
NREL	National Renewable Energy Laboratory
OFMSW	Organic Fraction of Municipal Solid Waste
PAH	Polycyclic Aromatic Hydrocarbon
PID	Proportional Integral Derivative
RMT	National union of Rail, Maritime and Transport Workers
RSSB	Rail Safety and Standards Board
RTTC	Reinvent The Toilet Challenge

RT	Residence Time
RPM	Revolution Per Minute
REV	Revolution
RSM	Response Surface Methodology
STS	Sewage Treatment System
SS	Sewage Sludge
SCCM	Standard Cubic Centimetres per Minute
TT	Train Tissue
TG/TGA	Thermal Gravimetry Analysis
VSS	Volatile Suspended Solids
WWTP	Wastewater Treatment Plant
WSUP	Water and Sanitation for the Urban Poor

Chapter One

1 Introduction

This Chapter provides a comprehensive overview of the topics necessitating this research project. Provided is an overview of the project and the aims and objectives of the project, the research question and details of the research design

1.1 Background

The rapid increase in population and urbanization growth has led to intensified environmental challenges including pollution and waste management. The escalating volume of wastewater is a direct consequence of the increasing waste. In general, wastewater could be sourced from any municipal, commercial or industrial processes [1]. Sewage sludge, a major solid by-product of mechanical, biological or chemical wastewater treatment, is the key concern due to its potential risks to human health and environment [2]. The majority of the solid constituents in sludge are those of organic, inorganic matters and living organisms which would result in a volatile and hazardous matter with toxic elements. Traditional methods for the treatment and disposal of sewage sludge include landfilling, composting and simple incineration. However, hazardous nature, high moisture content and low heating value of the sewage sludge in comparison to other wastes (e.g., biomass and fossil derived polymers) implies technical problems and increasing cost for their treatment [2].

In recent years, environmental protection directives and other sustainability measures have aimed for the reduction of landfills through promotion and enhancement of treatment technologies. For this aim, technology improvements for the reuse and recovery of sludge-derived products such as raw rare metals,

phosphorous, ash, chemical and organic fuels have been investigated [1]. Consequent treatments technologies for the stabilization of the organic matter (destruction of pathogens, odour elimination and reduction of volatile contents) researched for this purpose are mostly:

- Biological (composting or digestion)
- Physical (pressure, Thermal, vibration or microwaves)
- Chemical (oxidation, alkalinity adjustments)

Utilisation of these treatment methods is mostly for the improvement in the effluent quality, reduction in volume by nutrient recovery and/or safer disposal. However, well-established treatment technologies for sewage sludge remain limited to their capacities and capabilities to appropriately and economically meet legal and environmental regulations [1].

Reliability issues involved with the on-board train toilet facilities are known to cause problems for the operators. The traditional method of depositing the wastes (mainly human faecal sludge) generated from the toilet directly on the track is considered unhygienic and is criticized by the national union of rail, maritime and transport workers (RMT) and government [3]. Rolling stock built after 1988 have been fitted with a Controlled Emission Tank (CET), which needs to be regularly emptied and the freshwater tank to be replenished. This needs depot resources which can also mean constraints on train availability [4]. There are costs associated with the emptying of the CET and the replacement of freshwater tank for the reliability of the toilet. Primarily, those resulted from the train being taken out of service, and the fuel cost for shunting around the depot [3]. In overall, addition of the costs for the specialist staff to complete the procedure could increase the total figure in the order of £500,000/year.

The conventional water closets are comprised of a portable water tank that feeds both the basin and the flushing toilet shown in Figure 1-1. Following that, the output from these two are directed into the CET that is emptied in the depot by extraction pumps.

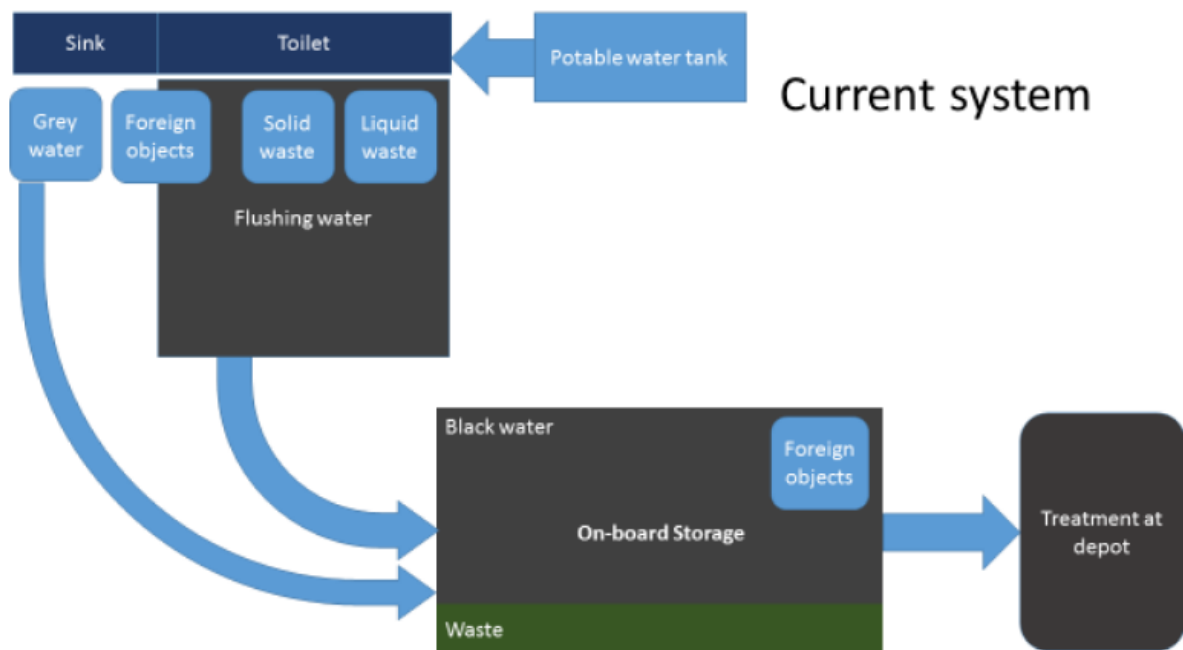


Figure 1-1 Wastewater storage in CET schematic [3]

Hence, in order to keep the rolling stock in circulation, the ideal sanitation system has to be capable of handling all the waste streams entering the CET in a hygienic and user-friendly way [3]. Different strategies for this aim have been followed:

- 1) Reusing the grey water in the first instances as flushing water that leads to less water consumption.
- 2) Reducing the amount of flushing water within utilisation of vacuum toilets.
- 3) Reuse of the flushing water that could potentially face customer's resistance.

Additionally, the other possible strategy chosen for this aim is to process and treat the waste streams on-board that could relatively reduce the frequency of depot visit for the train. This strategy refers to a stage during which the black water content (liquid and solids) in the CET is recovered or recycled within a rapid timeframe [3].

In 2016, Rail Safety and Standards Board (RSSB) requested a review of the sanitation technologies with the potential to close the water loop in the toilets. This research was carried out by IXC UK Ltd, with a particular focus on

technologies working in a closed loop fashion, where inputs and consumables can be reduced, reused, or recycled. This could potentially decrease the frequency of a train being taken out of service, which is known to be a key outcome from the industry point of view [3].

The research followed up an investigation carried out in 2007 by RSSB [4], assessed the technologies and scored their potential impacts. The majority of identified systems utilised anaerobic digestion principles within bioreactors (next) which are mentioned below:

- BFG international's Waste Recycling System (Bioreactor)
- EVAC's Sewage Treatment System (STS)
- AKW's Bioreactor
- Knorr-Bremse Group's Bioreactor Recycling System
- Semvac A/S Chemical Recycling Toilet System
- QinetiQ's Integrated Waste Processing System (IWPS)

The interest in these closed loop sanitation systems both commercially and academically, lies within the generation of energy in the form of methane or hydrogen. However, this might not be a priority for the rail industry, but technologies for recovery of wastes are able to provide energy for which the emerging projects are leveraging such energy for low carbon transport [4]. Of the six mentioned technologies, only the first two technologies have been continued based on their high impact and are currently marketed in the UK.

1.1.1 BFG international's Waste recycling system

An advanced waste recycling system for the rail market aiming for the reduction of water consumption and extension in maintenance periodicities was designed by BFG international. The concept has followed membrane bioreactor technology for which the prototype laboratory testing was completed. Different configurations have been considered for the technology with the limitation on water replenishment interval of 3 days, if the recycled hand-wash water option is not selected [4]:

- Waste treatment unit which dumps 'clean' water directly on the track
- Waste treatment unit which recycles water to operate toilet flush
- Waste treatment unit which recycles water to operate toilet flush with further treatment to raise water quality to drinking water standards to supply hand-wash system

The interval of the waste removal was extended to up to 6 weeks interfacing with existing depot infrastructure. Figure 1-2 illustrates the BFG international's waste recycling system.

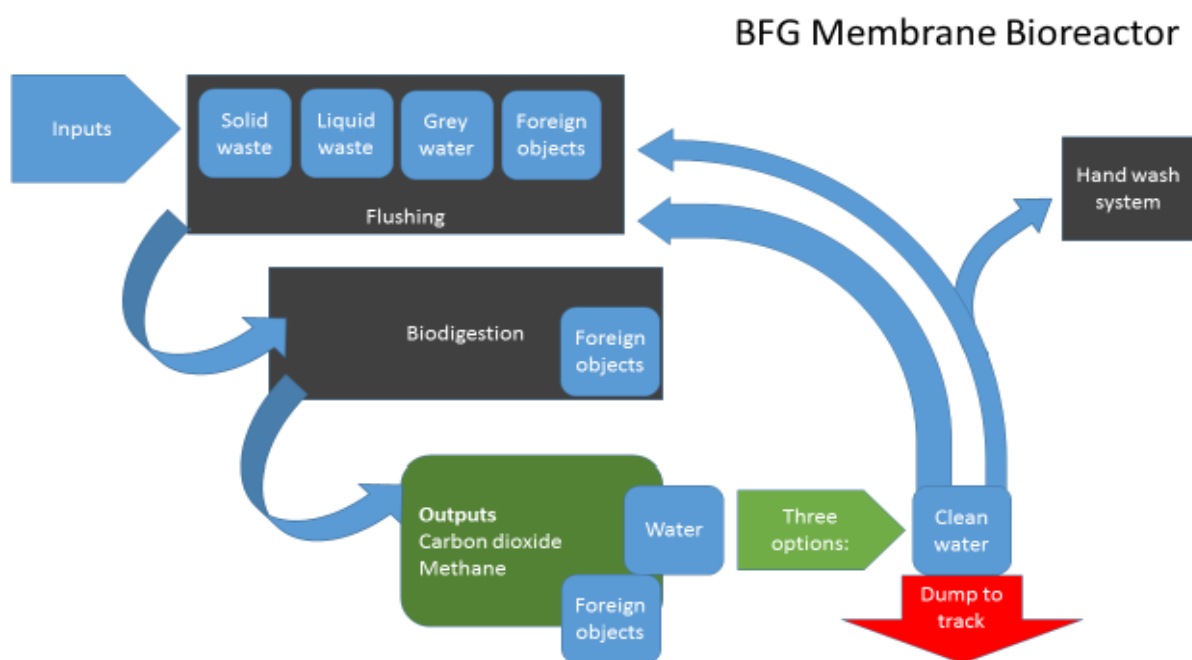


Figure 1-2 BFG international's waste recycling system [3]

1.1.2 EVAC's Sewage Treatment System (STS)

Using a patented electrolytic oxidation process, the organic waste is turned into water and carbon dioxide. This system, developed by EVAC, reuses the disinfected water for toilet flushing.

The wastewater is pumped through electrodes prior to which, the surface of the particles is enlarged utilising a macerator. An advanced electrolytic oxidation removes the organic contaminants, and the resultant water is stored in a

freshwater tank to feed the toilet flush. An advantage of this technology is that no chemical additives and sewage extraction equipment at the depots are required. Limitations on the electrodes replacement up to every 3 years and portable water supply for hand wash system replenishment in every 3-7 days is recorded for this technology [4].

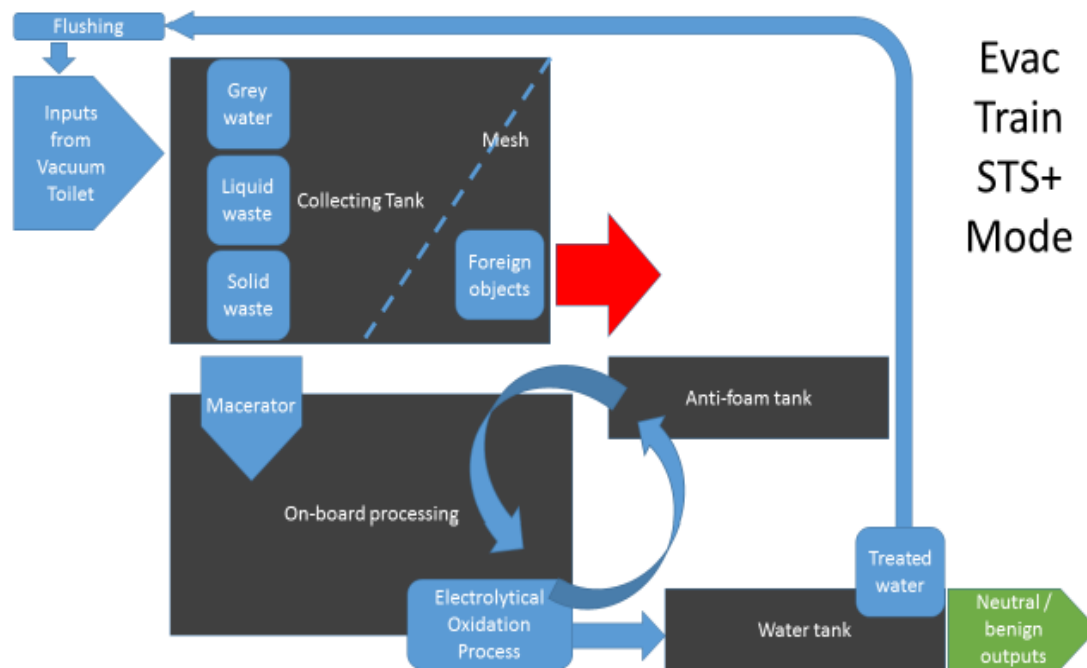


Figure 1-3 EVAC's sewage treatment [3]

1.2 Basis of this research project

Throughout the IXC UK Ltd. research, the specific criteria based on which the technological assessment was carried out, were considered as two themes with different sub-criteria:

Table 1-1 Technological assessment criteria

Applicability to rail	Whole life costs
Acceptability	Implementation
Translation to rail	Operational
Correlation to Rail Technical Strategy	Reduced visits to depot
	Reliability

Among all of the mentioned criteria, reduced visits to depot and the reliability were considered as the key points by the stakeholders which needed to be addressed. Results from the technological assessment for the two continued technologies mentioned in the previous section are shown below:

Table 1-2 Impact assessment on BFG and EVAC technologies [3]

Applicability to rail	Multiplier	Maximum score	BFG	EVAC
Acceptability	3	15	15	15
Translation to rail	4	20	20	20
Correlation to rail technical strategy	1	5	1	1
Whole life costs				
Implementation	5	25	15	15
Operational	2	10	10	10
Reduced visits to depot	10	50	50	50
Reliability	10	50	50	50

After this technological assessment, once again the necessity of a wastewater treatment system which could potentially meet all the criteria, recycle and recover the water on-board within a more rapid timeframe was highlighted.

In 2019, GBR-Rail Ltd., commenced a project under the name 'ClearTrack' in collaboration with Cranfield University for the development of a novel small-scale wastewater treatment system to be used in railway rolling stock. Recently, limitations on traditional methods of sludge disposal have diverted the interest in energy content of waste material. Anaerobic digestion as a biochemical extension of wastewater treatment for energy recovery has been followed by different companies as a solution for on-board train toilet's faecal sludge. One of the major disadvantages of the systems working with digestion principles is that the biogas (mainly methane) obtained at the expense of partial biodegradation of sludge is resultant from 35-50% break-down of COD/VSS [5]. The output of this biochemical reaction is a partially stabilized sludge which needs further management prior to disposal.

Another pathway for the energy recovery from sludge is known to be the thermal treatment methods. Thermochemical conversion routes such as combustion, gasification and pyrolysis provide the decomposition of organic matter (>80%) in a short reaction time ranging from seconds to min [6]. This reaction time for the anaerobic digestion could range from 7 days to 5 weeks whilst having a much lower efficiency [1]. Additionally, utilisation of thermal treatment technologies for the processing of sludge could reduce the volume of waste and stabilise the toxic organic compounds while fixing the heavy metals present.

The system utilises a water purification and a sludge treatment system shown in Figure 1-4 for the processing of the wastewater on-board. Biological conversion of sludge utilises the organic waste with high moisture (~98%) content without reduction in the calorific value of the produced biogas and so, lower cost. On the contrary, Thermochemical conversion technologies require lower moisture content (<30%) regarding the fact that the calorific value of evolved gaseous compounds from these processes is highly dependent on moisture content [1].

Therefore, the sludge undergoes a dewatering stage which delivers 25% solid matter in sticky phase and is followed by thermal drying to obtain <10 wt.% moisture content in dried granular sludge.

This PhD project focused on the sludge treatment and disposal process in the context of 'ClearTrack' wastewater treatment system.

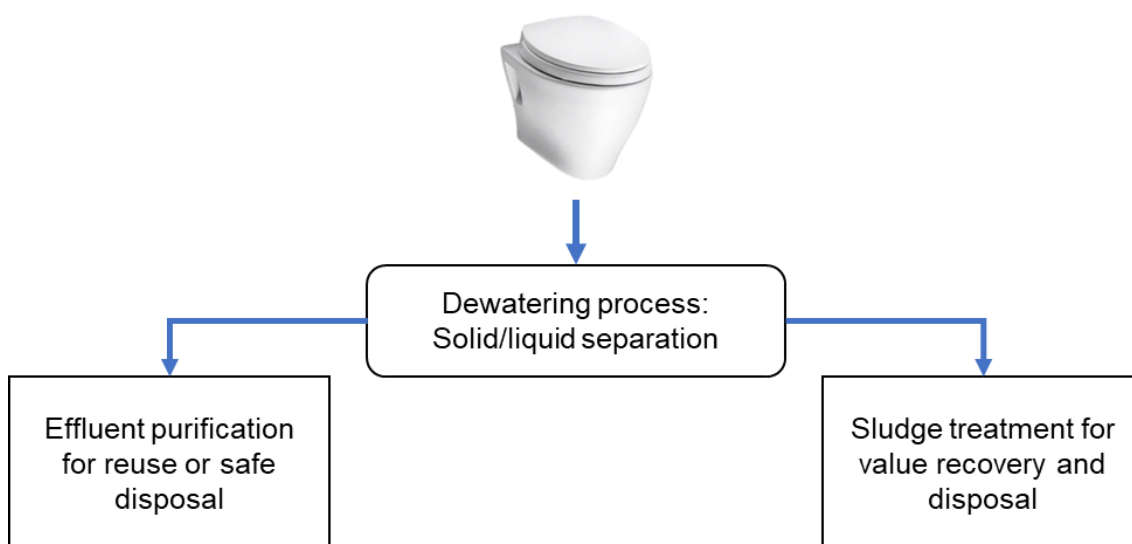


Figure 1-4 GBR-Rail Ltd. wastewater treatment system

1.3 Hence, production of an innovative small-scale thermal treatment system for the energy conversion and safe disposal of sludge is within the scope of this thesis project. Thesis overview

This thesis is formatted in the form of papers; thus, each experimental Chapter contains a standalone introduction, methodology, results and discussion and a conclusion. Chapter 2 of this thesis is peer reviewed and published, provided in Appendix H.

This Chapter aimed to provide an insight into the concept of ClearTrack initiative and the objectives of this thesis. Further Chapters address various stages of research and development of the solid waste management technology in the ClearTrack system. Finally, the conclusion Chapter summarises the findings of

this work and highlights the implications for future work. An overview of the overall thesis Chapters is provided in Figure 1-5.

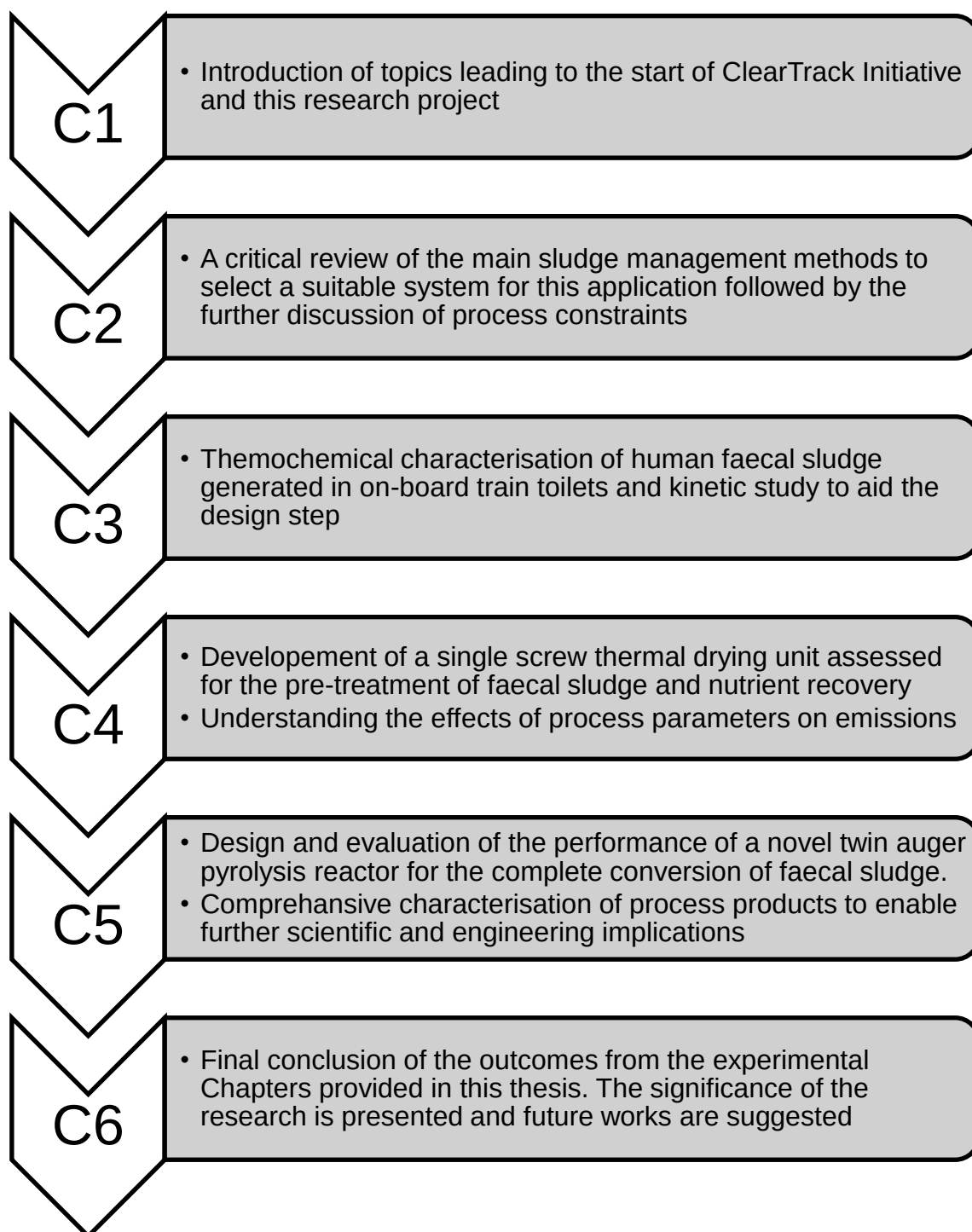


Figure 1-5 Basic overview of the PhD thesis

Chapter Two

2 Literature Review

This Chapter critically reviews the solid waste management technologies with a focus on the application of 3 main thermal treatment methods implemented in commercial and small scales to aid in the selection of robust conversion method for this application. Further constraints associated with the suitable process are discussed in detail and addressed.

This Chapter is published:

F. Beik, L. Williams, T. Brown and S. T. Wagland, "Managing Non-Sewered Human Waste Using Thermochemical Waste Treatment Technologies: A Review," *energies*, vol. 14, no. 22, 2021. <https://doi.org/10.3390/en14227689>.

Abstract

The utilisation of micro-scale thermal treatment technologies for non-sewered applications has been emerging as a prominent route for the safe treatment and disposal of high-water content hazardous feedstock. This study provides a comprehensive review of the technological concepts practiced up to date in commercial/pilot and small scales for various types of solid fuels. The respective challenges are critically described and discussed to aid in the selection of promising technology for on-site sanitary applications. Furthermore, the challenges observed with the nominated (pyrolysis) technology are discussed in detail and addressed. This study suggests rapid energy recovery from by-products primarily made up of the highest yield of syngas with a desirable calorific value. The optimum operating ranges are discussed to ensure a reliable thermal conversion of sludge materials considering the application constraints and

technology drawbacks. However, further studies are needed to investigate the uncertainties regarding emissions, energy consumption and overall associated costs.

2.1 Introduction

The overall aim of this research is to develop a novel solid waste management system to stabilise and convert the hazardous faecal sludge generated on on-board train toilets. For this, a critical review of the overall performance of the existing technologies implemented for solid waste materials is vital. Therefore, this Chapter narrows down and select a technology for ClearTrack application with respect to the constraints and further discusses the criteria for system development.

The human population produces a significant amount of sanitary waste every year, up to 55.1 kg/person/year, which equates to an overall figure of around 385 million tonnes per year for a global population of 7 billion [7]. Human excreta is a hazardous waste that needs to be managed safely. Faecal sludge (FS) is a generic term referring to the mixture of undigested or partially digested slurry/solids resulting from the storage or treatment of black water or excreta with or without grey water [8]. In general, faecal sludge management (FSM) includes storage, collection, transport and treatment in wastewater treatment plants (WWTPs) and the safe end use or disposal of FS [8]. However, FSM also relates to non-sewered sanitation systems such as pit latrines and septic tanks [9]. Several organisations such as the international sanitation community, Water and Sanitation for the Urban Poor (WSUP) and The Bill and Melinda Gates Foundation have supported initiatives with a focus on FSM challenges in low-income countries [10] [9] [8]. In contrast to FSM, sewerage sanitation is only concerned with wastewater/sewage treatment [11].

A typical wastewater treatment plant (WWTP) receives polluted wastewater from multiple sources, including municipal and commercial sources, in the form of water, human excreta, personal care products, etc. The two products of WWTPs are effluent and sludge, which need to be of adequate quality for disposal

according to the Urban Wastewater Treatment European Directive (UWTED) in the EU [12]. Common methods of the disposal of treated sludge are landfilling, land application as a fertiliser and combustion. According to Eurostat [13], two of the commonly used methods in the EU have remained as agricultural use and combustion. However, land disposal and combustion are subject to increasingly strict regulations due to pathogen risks, greenhouse gas emissions from microorganism activities due to inefficient organic removal and a large amount of flue gas emissions, respectively [14]. Details about the European parliament and council directives can be found in [15] [12]. Currently, the recycling of sewage sludge through agricultural lands is legal in the UK and accounts for almost 80% [16] of the overall volume. Land spreading is banned in some EU countries, such as the Netherlands, where combustion is favourable due to concerns over the safety of its use in farmlands [17]. These risks include the presence of pathogens such as *Escherichia coli* and *salmonella*, persistent organic pollutants, heavy metals and microplastics [18]. Hence, future resilience through the implementation of robust and sustainable treatment processes is of high importance to tackle associated challenges with such waste materials.

Despite several variations of WWTPs, most of them currently follow the same route for the treatment of wastewater/sewage sludge: (1) preliminary treatment, (2) primary treatment and (3) secondary treatment. An inevitable by-product of raw sewage treatment is the sludge generated from the primary and secondary steps. After removing large objects via straining with bar screens (preliminary step), the suspended solids in the water column settle at the bottom of the tank due to gravitational differences in the primary step. The sludge generated is a semi solid/slurry that includes 50–70% suspended solids, which is pumped toward the sludge treatment process. Further on, using biological processes, non-colloidal solids are removed, and organic constituents are stabilised, namely 'secondary sludge'. The generated sludge is further treated following the sequence of thickening and dewatering (centrifuge, plate press, belt press, etc.), conditioning (thermal, chemical) and final treatment (composting, combustion, thermal treatment, wet oxidation, etc.), storage (liquid sludge, dry sludge, ash)

and transportation for landfilling, agriculture or other uses, as depicted in Figure 2-1 [15]. All these methods aim for the stabilisation of the biodegradable fraction of the organic matter for reducing the risk of putrefaction, diminishing the concentration of pathogens, reducing weight and volume and odour elimination [19].

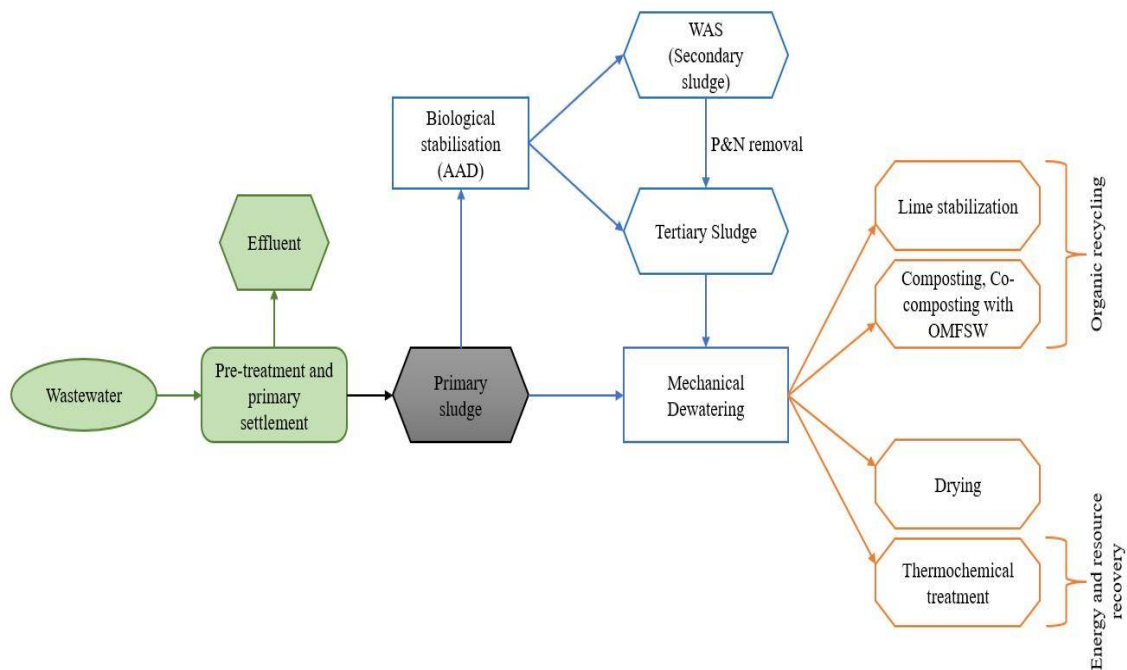


Figure 2-1 Sewage sludge treatment processes (AAD – Anaerobic digestion, WAS – Waste-activated sludge, OMFSW—Organic fraction of municipal solid waste) [15] [20] [21]

The characteristics of outputs from wastewater treatment processes depend on the production/treatment route pursued and the origins of the sewage. An example of a stabilisation technique for sewage sludge is anaerobic digestion in the secondary treatment step from which the product can be utilised as fertiliser. In addition, this process can recover energy by harnessing the biogas released from the digester [22].

One objective of this critical review is to discuss the solid waste management/stabilisation technologies and their operational challenges. The state of the art of these thermal treatment technologies for on-site, non-sewered,

sanitary applications in small scale is reviewed to clarify the specific operational challenges occurring through their implementation. The aim of this study overall is to outline the challenges for developing a suitable technology for on-site sanitary applications and to address optimum ranges of operating conditions for a reliable performance.

2.2 Sewage Waste/Biomass Treatment Technologies

2.2.1 Anaerobic Digestion

Anaerobic digestion is a biological conversion process of organic compounds in an oxygen-free environment, producing biogas using microorganisms. The ability to utilise organic feedstock with a high moisture content without reducing the calorific value of the produced biogas is a major advantage of this technique. However, the reaction time ranges from 7 days to 5 weeks and the conversion efficiency of organic constituents from 30–60%; this is not sufficient for agricultural applications regarding their high organic content and poor biodegradability [1]. Digestate from the anaerobic digestion of sludges is still likely to pose biohazardous and other risks due to microplastics [18]. In addition, the volume of the treated sludges through biological means is observed to reduce only 5% of the original mass of sludge [23]. Dewatered sludge can be directly fed into the digester for biogas recovery; however, the high organic content of the digestate has emphasised the utilisation of a pre-/inter- and/or post-treatment step for maximum energy recovery and volatile organic conversion [24].

The overall aim of sludge treatment is to achieve the effective elimination of organic matter and a high recoverable energy content of sludge (11.10–22.10%) [25]. Therefore, thermal treatment technologies have proven to be attractive for resource and energy recovery, treatment and disposal of sewage sludge (SS).

2.2.2 Conventional Combustion

Thermal treatment processes include combustion and the emerging gasification and pyrolysis technologies. In comparison to anaerobic digestion, thermochemical conversion routes provide much shorter reaction times for the

treatment of sludge (seconds to minutes). However, these processes require sludge with a lower moisture content where the decomposition of >90% of the organic matter occurs in the presence of a surplus oxygen, partial oxidising or anoxic (minimised oxygen) environment.

Combustion is used for medical and municipal waste [26]. Combustion is currently used for heat recovery from sewage sludge with the incorporation of a heat recovery step in the treatment process, but the traditional practice was only intended for a reduction in the volume and the elimination of harmful elements [27]. Combustion takes place at high temperatures (800–1150 °C) in the presence of surplus oxygen for the complete oxidation of organic matter, which delivers the transformation of carbonaceous materials into a flue gas consisting of oxides of carbon, nitrogen, sulphur and particulate matter, while releasing a substantial amount of heat and other trace gases and H₂O. Multiple hearth furnace (MHF) and fluidised bed (FBF) are the two common reactor types utilised for sewage sludge combustion, of which the MHF is suitable for wet sludge while the FBF is used for both wet and dried sludge. A major barrier for the cost and process efficiency of sludge combustion is the moisture content of sludge with the acceptable limit of <50% [28]. Hence, dewatered sludge undergoes a drying step after the dewatering stage to increase the calorific value of the fuel for thermal processing [25]. A high moisture content results in incomplete combustion as well as heat loss from the evaporation of the moisture content [28]. Additionally, it reduces the energy content of the sludge to 4 MJ/Kg (60–80% moisture content), which is inappropriate for autothermal combustion [29]. Therefore, this process is usually associated with the utilisation of auxiliary fuel and catalysts for the initiation and further reaction stability. This process offers a reduction of up to 90% in the volume of sludge, leaving an inert material (ash) for disposal. This is a potential product and could be used for the production of building materials [21]. A high ash content in SS is also thermally parasitic, which leads to incomplete combustion, thus forming a variety of pollutants such as polycyclic aromatic hydrocarbons and dioxins [30]. The high inorganic constituents in sewage sludge ash such as alkali-induced metals also cause

further challenges such as slagging and agglomeration. A major challenge for the combustion of sewage sludge is the elevated amount of NO_x , SO_x , etc., which could be sourced from human activities (e.g., faeces) [31]. Different researchers investigated the pollutant emission of sewage sludge combustion, concluding a reduction in the concentration via lower combustion temperatures [25] and co-blending [32] for NO_x and SO_x , respectively. In a study by Han et al. [28], it was observed that SO_2 could also react with the water in the wet sludge and lead to the formation of H_2SO_3 , a corrosive compound for metal surfaces. Although analysis on the concentration of heavy metals in the past studies on SS combustion revealed modest percentages below legal limitations, these studies still implicated the utilisation of efficient gas cleaning systems to capture the heavy metals present in the particulate matter and highly volatile species (e.g., Hg, Cd and Pb) in the vapours [33] [34]. To address the problems mentioned above, recently there has been an increasing interest in an emerging method named 'co-combustion' by combining sewage sludge with other high-rank energy fuels such as biomass and coal [30].

2.2.3 Emerging Methods

Although combustion leads to a major reduction in the volume of sludge, the large amount of flue gas generated through the process incurs a high cost for their treatment as well as high energy consumption for pre-drying. Wand et al. [35] reported that the development of co-combustion with a slight modification in conventional combustion equipment for sludge has taken precedence over pyrolysis, gasification and mono combustion in large scales.

2.2.3.1 Co-Combustion

Co-combustion has been considered as a new route for net CO_2 reduction in sewage sludge valorisation. The utilisation of co-combustion/blending has mainly aimed for improving combustion reactivity and reducing pollutants and greenhouse gas (GHG) emissions. In a study by Rong et al. [36], a synergetic interaction between the rice husk and sewage sludge co-combustion was observed, while the reactivity between the blends was improved when the SS

proportion remained <30 wt.%, resulting in the production of an ash with lesser slagging potentials. Moreover, Wang et al. [35] investigated the combustion behaviour of sewage sludge (SS) and wheat straw (WS) co-blending, where the combustion characteristics of SS were enhanced with the highest synergetic interaction in the presence of 50% WS.

2.2.3.2 Advanced Thermochemical Treatment (ATT)

The thermochemical conversion of sewage sludge is a promising alternative to biochemical practices due to its ability to decompose almost all organic parts (biodegradable or non-biodegradable) in a short period. In addition, there has been great interest towards the valorisation of sewage sludge and municipal waste into oil and synthetic gas via pyrolysis and gasification [27]. Advanced thermal treatment technologies are also capable of reducing the volume of waste, degrading hazardous organic matter and recovering hydrocarbon compounds from the residues rather than heat only. Additionally, the risk of producing dioxins, furans, SO_x and NO_x could be mitigated via restricting the environment in ATT processes [14].

2.2.3.2.1 Pyrolysis

Pyrolysis, together with the evaporation of bound moisture, is an initiating step in all thermochemical conversion processes occurring at moderate temperatures (350–600 °C) in an inert (non-reactive) environment. The decomposition of SS (organic matter) through this process results in the production of liquid pyrolytic oil (condensable volatile fraction), pyrolysis gas (non-condensable volatile fraction) and char (solid residue) [37]. The liquid pyrolytic oil has been upgraded for combustion in boilers or engines as well as electricity production [38]. The biochar derived through pyrolysis has been utilised as a solid fuel, an adsorbent for decontamination, a fertiliser for soil amendment and briquetting [20] [39] [40]. However, the char from sewage sludge has not been found suitable for heat recovery owing to its low heating value (5 MJ/kg) as well as the presence of a high concentration of heavy metals, which restricted its landfilling [37]. To address the challenges with the utilisation of char, researchers have focused on improving

the quality of the char for soil productivity and the remediation of contaminants via feedstock chemical impregnation [41]. The syngas generated through thermal cracking of the tar in high temperatures (secondary reactions) is used in internal and industrial combustion engines [42]. Depending on the various operational parameters such as the heating rate and residence times, pyrolysis is classified into three main categories, namely slow, fast and flash pyrolysis [43]. Slow heating rates (0.1–1 K/s) and long residence times favour the formation of char [39], while lower or higher residence times in high temperatures with high heating rates result in liquid and syngas production, respectively [1]. Table 2-1 illustrates the process conditions in different pyrolysis modes where the residence times of volatiles for slow/intermediate, fast and flash pyrolysis are 10–30, <2 and 0.5 s, respectively [44]. Conventionally, fast pyrolysis has been used to produce pyrolytic oil, whilst slow/intermediate pyrolysis has favoured the formation of char and non-condensable combustible fractions. High heat influx involved with fast pyrolysis, as well as substantial heating rates for the rapid decomposition of dry matter, faces complexities regarding the pre-processing of the feedstock. Pre-processing includes operations such as particle size reduction and efficient drying to a range of 10% moisture content [45]. Park et al. [46] observed that larger particles in the sewage sludge led to incomplete fast pyrolysis due to a lack of uniformity. The liquid pyrolytic oil, especially the organic fraction, from fast pyrolysis contains a high heating value of ~33 MJ/kg, which makes the fast modes of more interest compared to slow pyrolysis. Hence, most previous research focuses on the production of bio-oil within fast pyrolysis of sewage sludge [27]. The production of pyrolytic oil through this process requires fast vapour removal and quenching to mitigate the chance of secondary reactions, resulting in the breakdown of longer chain species with high molecular weight to light gaseous products [46].

Table 2-1 Classification of pyrolysis process [43] [47]

Pyrolysis Process	Temperature (°C)	Heating Rate (°C/min)	Solid Residence Time (s)	Particle Size (mm)	Product Yield (%)		
					Oil	Gas	Char
Slow/int	400–500	10	~500	5–50	30	35	35
Fast	400–650	100	0.5–10	<1	50	20	30
Flash	700–1000	>500	<0.5	<0.2	75	12	13

Product diversity and distribution are mainly dependent on process temperature, operational modes, reactor configuration and feedstock characteristics [5]. Different reactor designs have been established for pyrolysis depending on the desired final output (e.g., heat, electricity, liquid, syngas and/or char) as well as feedstock characteristics. For instance, fluidised bed reactors have been found suitable for the fast pyrolysis of biomass in commercial applications regarding their good temperature control and efficient heat transfer [47] [44].

The chemical reactions taking place during pyrolysis are endothermic and are pursued in an inert (non-ignition) environment by means of external heat source. Hence, to address the energy intensity of pyrolysis, research on the partial/complete combustion of syngas and pyrolytic oil for the self-sustainability of this process has been carried out [48] [49]. Since the desirable product from pyrolysis (mainly fast and flash modes) is the bio-oil, <10% moisture content [23] in the feedstock has been considered suitable for fast pyrolysis, which implies greater energy consumption for pre-drying in comparison to combustion. A high-water content has been known to be disadvantageous for the energy content and combustion characteristics of bio-oil [50]. Although the pyrolysis of raw sludge (moisture content of ~70–80 wt.%) leads to a significant condensed water fraction in the bio-oil, this method has been found to be suitable for the generation of hydrogen-rich non-condensable gases via in situ steam reforming of the volatile compounds and partial gasification of the char [51]. Dominguez et al. (2006)

stated that the pyrolysis of wet sewage sludge provides a higher gaseous fraction with significant hydrogen content within the combination of pyrolysis and gasification due to the presence of water in the reaction atmosphere compared to the pyrolysis of dried sludge [52]. To conclude, high-water content as a major challenge for the production of bio-oil cooperates with the self-sufficiency issues of pyrolysis for the limitation on the commercialisation of pyrolysis. However, opportunities for the usage of pyrolysis in large resource recovery applications from dried sludge are predicted [37].

An advantage of pyrolysis over combustion and gasification is that the emissions include lesser pollutants (e.g., heavy metals, dioxins, furans). Conesa et al. (2009) investigated the effect of temperature and oxygen on the emission behaviour of different wastes including sewage sludge, where it was observed that the concentration of furans was increased along with an ascending oxygen ratio [53], whereby polyaromatic hydrocarbons (PAHs), which were formed through pyrolytic conditions, followed a negative trend with the oxygen increase. Analysis on the temperature effects also revealed a maximum point at temperatures of about 750–850 °C under pyrolytic conditions. In contrast, the PAH concentration under combustion conditions was also maximised at ~800 °C. This could indicate less pollutant emission because of the lower operating temperature of pyrolysis. Moreover, Jin et al. (2016) analysed the behaviour of heavy metals during the pyrolysis of sewage sludge and concluded the retention of the majority of them in the char, resulting in enhanced bioavailability and thus lower risk to the environment [39].

2.2.3.2.2 Gasification

Gasification is an extension to the pyrolysis process in which the resultant gas and solids (char) from pyrolysis undergo further reactions in the presence of 20–40% oxygen needed for combustion. The temperature through this process ranges from 700–1000 °C, where the formation of light combustible gases (syngas), such as H₂ and CO and other gases (i.e., CO₂, CH₄), from the gasification of the carbonaceous content (char) takes place [20]. This process

involves two more core stages after drying and pyrolysis, where the partial oxidation of the char and volatiles takes place involving a gasification agent such as air, CO₂ and steam or a combination of these (e.g., air–steam or steam–O₂). These stages result in the gasification/reduction of the char via the heat generated from the exothermic oxidation reactions in ~1100 °C. The resultant heat from the partial oxidation stage also supplies the energy for drying and pyrolysis, which implies the self-sustaining behaviour of the process. However, the acceptable moisture content limit suitable for in situ drying of SS during gasification is less than 20 wt.% [1]. Moreover, due to restrictions on the reaction environment, the formation of SO_x, NO_x, heavy metals and other aromatic compounds is minimised [37]. The syngas obtained from this process is typically used for heating or electricity generation, or further processed for chemical or liquid fuel synthesis [27].

The product yield, quality and the process completion because of complex sequential thermal decomposition reactions in various stages throughout the process are dependent on the gasification medium, gasifier type, reaction conditions and feedstock composition. Among several types of gasifier configurations, fixed-bed downdraft, fixed-bed updraft and fluidised bed reactors have been investigated for sewage sludge [27] [54]. The difference in an updraft and downdraft configuration is mainly in the introduction mechanism of the gasification agent into the reactor. In an updraft configuration, the gasification agent enters the reactor from the bottom and the feedstock falls from the top, resulting in rapid oxidation of the char from pyrolysis reactions. Following that, the hot gases exit the reactor from the top, potentially carrying high concentrations of tar. However, in a downdraft configuration, the gasification medium is introduced from the side, which descends within the contact with the pyrolysis products. This configuration facilitates the reduction mechanism of the char via further heat transfer in the char bed. The overall energy efficiency of the updraft design is higher compared to the downdraft design, owing to the efficient heat transfer between hot gases between volatiles, char and sludge in the reduction, pyrolysis and drying zones, while the hot gases exit the reactor in high

temperatures. However, the tar content of the syngas (producer gas) as a bulk criterion is lower in comparison to the updraft design [45]. Although keeping moisture content in the range of >20 wt.% is preferable due to heat losses and the energy consumption of water vaporisation during gasification, the two reactor designs can handle higher moisture contents up to 50% in optimum reaction conditions [27]. Moreover, fluidised bed reactors have been utilised to address the challenges regarding uniform heat transfer and temperature distribution in the reactor via introducing the gasification medium in a suspended form fluidising gas.

2.2.4 Review of Comparative Assessment Studies

Several researchers have published comparative studies on the thermochemical conversion of sewage sludge to aid in the selection of a sustainable technology for sewage sludge management [37] [1] [55]. The objective of these publications has been to review the literature and compare the thermochemical conversion technologies either qualitatively or by using a comparative method (SWOT, FAHP, etc.). However, the conclusions from these studies differ since various technical criteria are applied in each study. The ranking mechanisms in previous studies are affected by the environmental regulations and technological development corresponding to the geographical zone in which the study was carried out. A critical review of these publications indicated that among combustion, gasification and pyrolysis as the main thermal treatment routes, pyrolysis could potentially provide a more sustainable approach towards sewage sludge management. This finding is a result of reduced pollutant emissions and zero hazardous waste disposal goals achieved through this technology. Nonetheless, the advantage of this technology is offset by intensive energy consumption for pre-treatment/drying that needs to be addressed to fulfil sustainability goals [37].

2.2.5 Review of Micro-Scale Human Faecal Sludge/Faeces Treatment Studies

Recently, there has been a great shift in interest towards the utilisation of small-scale thermochemical conversion technologies for sanitation [56] [57]. The on-site sanitation approach for non-sewered communities (low-income countries) or parts of developed countries where sewage infrastructure is inaccessible/difficult is identified to aid in the promotion of faecal sludge management [58] [59]. Some of the features of this approach are restrictions on the finances for storage and transportation, potential energy recovery from natural resources and mitigation of the risk of non-optimal disposal of human faecal waste in the environment. Indeed, the physical and chemical characteristics of the solid waste (mainly faecal matter and/or tissues) generated and stabilised through these decentralised wastewater treatment systems are different from those stabilised in commercial/pilot-scale wastewater treatment plants. Most of the research in this area has been conducted in response to initiatives such as Bill and Melinda Gates' 'Reinvent the Toilet Challenge' (RTTC) [8] [9] [60]. The innovative sanitary systems built under this initiative are required to operate in a waterless mode, whilst pursuing sustainable operation from the energy intensity point of view by recovering energy from solid waste [56]. Meanwhile, the micro-scale thermal processing systems in these contexts are designed to handle human waste in households of ten people considering the average input rates of 200 g per capita per day [56]. In response to this initiative, researchers at Cranfield University developed a novel sanitary system 'Nano Membrane Toilet' (NMT), for which extensive research on the utilisation of thermal treatment methods for human faeces was undertaken [56] [58] [61] [59].

The gasification of dry and moist human faeces via thermodynamic modelling at the optimum equivalence ratio (ER) has been investigated [61]. Authors observed a decline in the content of exergy obtained from moist faeces (max 15 MJ/kg) at the optimum equivalence ratio and temperatures compared to dried samples (24 MJ/kg). The high moisture content of faecal samples was identified as 'parasitic' to gasification since the optimum point for thermal cracking was studied to be

near combustion conditions (equivalence ratio of 0.55–0.62). As a result, the heat generated through gasification was absorbed by water vaporisation reactions and the ignition and subsequent conversion processes were delayed. Overall, this study reveals the exergy deficiency of moist faeces' gasification, as the generated heat and the exergy of the syngas were not sufficient for in situ drying, implying the necessity of energy-intensive pre-drying of the feedstock.

In another study, a bench-scale downdraft combustor was used to evaluate the optimum conditions for converting faecal biomass to energy through combustion [59]. The combustion characteristics of dry and moist faeces were evaluated under different conditions (i.e., air-to-fuel ratio, moisture content, etc.). Preliminary results from the combustion of simulant faeces showed a moisture limit handling of 60% with a bed temperature of 600 °C. The optimum combustion conditions for various dried faeces were characterised as (1) a minimum bed temperature of 600 °C and (2) 16 L/min airflow rate. The tests were performed using 50–75 g of wood biomass to ensure the optimum bed temperature followed by an addition of 50 g of faecal samples. However, the results revealed the failure of the tests in the case of moist faecal samples due to the non-definite form of faecal samples. Different shrinkage rates in faecal samples representing different moisture contents were observed to result in the partial drying of faeces without ignition. To confirm, this physical characteristic of human faeces was found to decrease the front combustion velocity dramatically from 2.18 to 0.72 mm min⁻¹ where shrinkage was high [62]. Evaluation of the effects of fuel pellet size during combustion by [59] indicated a poor carbon conversion efficiency and a reduction in the process temperature attributed to improper interaction between the biomass material and hot air.

Findings from the study by Onabanjo et al. (2016) were used to successfully commission a novel micro-combustor capable of operating in downdraft and updraft modes under continuous feedstock flow conditions [58]. In contrast to the 2016 study, the continuous mode of operation was followed to limit the energy requirement for ignition and to keep the combustion bed at a sufficient temperature for incoming faecal material. The aim was to convert human faeces

with the lowest possible temperature to ensure energy efficiency and to reduce the heat loss through combustion. Ultimately, the heat generated was used for the pre-drying of the feedstock or the other energy consumer with the NMT concept. The optimum temperatures for sustained fuel ignition and steady-state operation of the reactor were estimated as 220–240 °C for dried faeces and were generated using an air igniter. The authors stated that the spark device as a part of the ignition system was not necessary as the temperature reached 400 °C. The dominant challenge with the self-sustainability of combustion was the fuel feeding rate at this small scale, which caused two operational problems:

1. Incomplete thermal conversion as the interval between each feeding was delayed for longer than 2 min, mainly due to the scale of the process with an optimum 1.2 g/min feed rate.
2. Blockage in the feeding system due to char production at the reactor's inlet; The authors suggested that further research for the optimisation of the micro-combustor for self-sustained combustion should be carried out [58].

A summary of the reviewed benefits and drawbacks associated with the main sewage waste stabilisation technologies throughout this study is provided in Table 2-2. The contents aim to highlight the overall performance of each technology, implemented in various scales, to facilitate the selection of a method for the decentralised treatment of human waste in micro-scale sanitary applications.

Table 2-2 Qualitative Comparison of sewage Waste Stabilisation Methods

Main sewage sludge stabilisation methods				
Biological		Thermochemical		
Anaerobic Digestion (AAD)	Combustion	Gasification	Pyrolysis	
Advantages	• High-water content of solid waste has no impact on the calorific value of biogas • Cost efficient technique • Simple by-products for end-use (Methane for energy recovery and stabilised sludge as fertilizer)	• Major reduction in the sludge volume (~90%) • Complete pathogen removal and sterilization • Chance of energy recovery	• High efficiency energy recovery • Lower environmental emissions due to production of 'cleaner' syngas • Major volume reduction (~95%) • Complete pathogen destruction and sterilization	• Takes place under inert environment – no need for fuel ignition using auxiliary fuels • Pathogen removal and sterilization • Low sensitivity to the feedstock physical properties (moisture content, particle size, etc.) • Low emissions due to absence of oxygen • Retention of inorganics and metal content in the char fraction • Lower heat fluxes – robust reactor operation • Chance of energy recovery from products

Disadvantages	• Very long processing timeframes • Limited conversion of organic matter (30-60%) and poor energy recovery • Non-efficient elimination of hazardous fraction in sludge • Limited reduction of sludge volume	• Lack of regulations • Requires ignition with the aid of auxiliary fuel • Needs fuel pre-treatment and moisture reduction • Extensive emission control needed • Operational complexities due to the ash and particulate matter • Very high heat fluxes with reaction area	• Need for moisture content reduction • High sensitivity to the physical properties of the feedstock • Need for ignition – auxiliary fuel • High heat fluxes present in the reactor • Inadequately practiced • Need for gasification agent – constraining implementation • Tar production	• Requires fuel pre-treatment (drying) • Energy intensive process • Inadequately practiced • Delivers by-products to be handled • Lack of regulations
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2.3 Discussion

A critical review of previous work completed on the subject of thermochemical treatment reveals the technical challenges associated with the implementation of 3 main thermochemical processes for various types of biomass and waste materials. Furthermore, a detailed analysis on the research completed for the development of on-site sanitation technologies highlighted the necessity of highly accurate process control and the optimisation of gasification/combustion. This has been due to the need for proper in situ ignition of the fuel, which is highly sensitive to the moisture content, feedstock flow rate, fuel physiochemical characteristics and the design of the reactor. Hence, the suitability of thermal conversion systems for sanitation depends on the capability of the system to handle alternative feedstock flow rates with different shrinkages and moisture contents. In this study, pyrolysis is selected as the promising method for on-site

sanitary applications, and further on, a comprehensive discussion on these processes will be conducted. Overall, research on the thermal conversion of human faecal waste is very scarce and a huge gap on the optimisation, emission rates as well as net energy balances of these processes is still in the literature.

2.3.1 Energy Consumption

The thermochemical conversion routes practiced commercially for sewage sludge as the most similar material to human faecal waste and other biomass types are depicted in Figure 2-2.

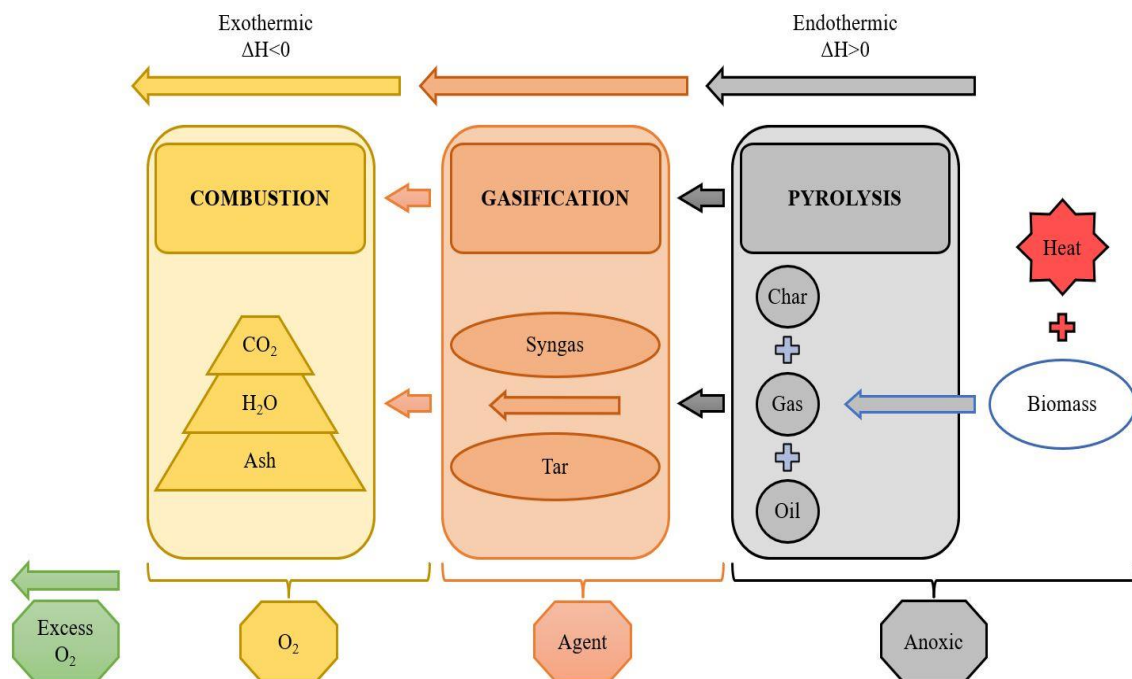


Figure 2-2 Three common thermal treatment routes [63]

For a combustion process, the chemical reactions corresponding to each step occur sequentially with some overlaps delivering different inputs for the following step with various energy contents. However, these processes are well distinguished from one another owing to the presence of oxidising agents in different concentrations during each stage [63]. Hence, the net energy balance analysis of each thermal treatment process is different and difficult to be compared with others regarding the: (1) complex sequential endothermic and exothermic reactions and (2) the variety in the energy content of the products in

the outputs. It is notable that a positive/negative net energy balance for these processes does not consider the drying process. The initiating drying process is a complete endothermic step for the vaporisation of the water content in biomass/waste requiring a substantial amount of energy, such as 3.4 MJ/kg in typical dryers with non-unity efficiency [64].

In the context of sanitary applications, for the implementation of a successful thermal conversion system in an application where extraneous energy is available for the completion of treatment, pyrolysis could still be an option. As depicted in Figure 2, pyrolysis is an energy-intensive process in contrast to gasification and combustion since the endothermic non-spontaneous reactions are predominant in this step/process. In the case of sewage sludge, pyrolytic reactions were found to be mostly endothermic in the order of 100 kJ/kg, whereas the exothermicity of oxidative reactions was found to be in the order of 10,000 kJ/kg [65]. To further elaborate, net energy positivity/negativity could be defined as the energy released from the exothermic reactions or available in the energy-rich products of each process, being less than, equal to, or more than the energy needed to complete the endothermic reactions in each process.

For pyrolysis, researchers have explored the sensible heat to bring reactants to pyrolysis temperature, the heat of pyrolysis and the sensible heat for product evolution, all together known as the enthalpy for pyrolysis [66], for different types of biomass and sewage sludge using different methods, shown in Table 3. Daugaard et al. [67] estimated the enthalpy for two types of wood as well as two herbaceous materials ranging from 0.8 ± 0.2 MJ/kg for oat hulls to 1.6 ± 0.3 MJ/kg for pine. The method utilised in this study covered a comprehensive analysis on the energy inputs and outputs within the reactor accompanied by inaccuracies in the estimation of heat loss within the range of 16–17.5%. In another study, the heat for the pyrolysis of birch dowels in dry and moist (55 wt.%) conditions was determined as 2.9–3.5 MJ/kg and 8.1–8.6 MJ/kg [66]. Further studies investigating the enthalpy for the pyrolysis of biomass and waste are summarised in Table 2-3.

Table 2-3 Enthalpy values and net energy assumptions for the pyrolysis of various biomasses and sewage sludges

Waste Type	Enthalpy (MJ/kg)	Moisture (%)	Description	Ref.
Oak Oat hulls Pine Corn stover	1.46 ± 0.28 0.78 ± 0.20 1.64 ± 0.33 1.35 ± 0.28	8.0 10.2 7.5 8.8	Pilot-scale fluidised bed pyrolysis reactor operating at about 500 °C.	[67]
Birch dowels	2.9–3.5 8.1–8.6	0 55	‘Water tracer’ technique was applied for the determination of the time of pyrolysis for a dry and an identical moist particle. However, this non-conventional method is known to result in errors within calculation [67].	[66]
Wood chips	0.7	5.9	The analysis of the enthalpy of pyrolysis was performed on a multiple-hearth reactor. An empirical method ‘P.D.U.’ was used to show the difference between electric energy consumption prior and through wood feeding.	[68]
Cedar, Pine, Willow, Bamboo, Sasa bamboo	1.3 ± 0.2 1.5 1.5 1.5 1.6	0	Enthalpy for the pyrolysis of five different types of biomass materials was calculated using a screw feeding reactor. The analysis aimed for the determination of the enthalpy of the formation of products based on their composition. However, the method used for the enthalpy of bio-oil included errors.	[69]
Willow chips	1.17	9.1	Analysis on conventional and microwave pyrolysis (required electricity).	[70]

Recently, several studies reported a self-sustainable pyrolysis to be achievable through theoretical combustion of the pyrolytic products. Typically, a low heating value of the non-condensable fraction has made it more suitable for heating the unit [71]. For sewage sludge, McNamara et al. (2019) found the energy content of pyrolytic gas and oil to be always sufficient for the pyrolysis process using the theoretical heat capacities of the constituents [64]. In another study of sewage sludge pyrolysis [72], the available theoretical heat of combustion for domestic sewage sludge was determined as 825 kJ/kg. This suggests higher recoverable energy from the non-condensable fraction of syngas in comparison to the heat required (730 kJ/kg) for the pyrolysis of the same type at 500 °C. For the two other types, excessive energy through the combustion of the bio-oil fraction was suggested for the self-sufficiency of the process. However, the analyses were all performed on dried sludge solids with 5.7% moisture content. Furthermore, analysis on the five different types of dried biomass by [71] indicated a self-sustainable pyrolysis to be feasible. The available enthalpies for pyrolysis in the literature in a range of 6–15% of biomass HHV were used. The authors observed that, considering the upper limit (15% HHV of biomass) as the enthalpy for pyrolysis, the process gas yielded at a high treatment temperature of 650°C could only surpass the enthalpy in some cases.

Taking the completed analyses on the energy efficiency of pyrolysis into account, the commercialisation of pyrolysis is still criticised by some researchers. Rollinson and Oladejo (2019) stated that a self-sustainable pyrolysis process is practically implausible and thermodynamically unproven. The authors highlight the importance of considering pre/post-treatment energy demands as well as proper thermodynamic considerations repetitively [73].

In the context of sanitary applications, addressing a gap on the heat required for the pyrolysis of human faeces/faecal sludge is necessary. This could be followed by an analysis on the conditions to produce maximum yields with the highest calorific value of py-gas and py-oil to address the net energy balance of this system. In a study on the pyrolysis of human faeces, Yacob et al. (2018) investigated the effects of heating rate and HHT on the yield and energy content

of the non-condensable fraction of syngas (py-gas) including CH₄, CO, CO₂ and H₂ as well as ethane. The promising conditions were evaluated as an operating temperature of 450°C and a heating rate of 2.5 °C/min, which provided 22.8 MJ/Nm³ and 29.6% gas mass yield, respectively [57]. However, in this study the analysis was performed on dried human faeces. To limit the energy consumption of a system implemented for sanitation, the recoverable exergy of syngas is of concern. An analysis on the total exergy of the syngas from the gasification of human faeces showed that moisture content could increase the exergy from 19 to 22 MJ/kg at an ER of 0.55 [61]. The moisture content limit was also observed to increase within progressive ER but at the expense of total exergy loss of the syngas, up to a point beyond which the exergy potential reached a lower extent than the gasification of dry faeces at the optimum point. Hence, the operating range at which the pyrolysis system can accommodate the highest moisture content is essential to reduce the energy needed for pre-drying.

Lastly, the pyrolytic char produced from such a system could also be used for energy recovery through combustion. To maximise the yield of the non-condensable fraction, high heating temperatures are required. Analysis on the product distribution of different biomass types showed a higher yield of combustible species such as H₂ and CH₄ occurring at temperatures $x > 550$ °C in most cases with a lower heating rate [71]. In the case of human faeces, this operating range was at ~550 °C [57]. Though at this HHT, the yield and energy content of the char reduce to half [71]. Ward et al. (2014) observed the faecal chars made at 750 °C having 13.8 ± 0.48 MJ/kg, which was much lower than those made at 350 °C with 25.6 ± 0.08 MJ/kg [74].

2.3.2 Technology Development

Prioritising a solution to address the issues observed with the energy intensity of a pyrolysis system, the operational reliability of the system needs to be considered carefully to ensure a safe and continuous functionality. This would then allow the transfer of such a system, not only for on-site processing in non-sewered applications, but also for mobile applications where the least

maintenance is desirable. To achieve this, a novel design for the pyrolysis system should be proposed to meet the expectations regarding the energy intensity, technology robustness, application constraints and the safe disposal/emission of its by-products. The innovative design of such a pyrolysis system should include an immediate energy recovery step from the by-products, overly controlled by various factors such as the fuel properties, the process conditions and the mechanical design. These factors are interrelated where the immature selection/planning of each could lead to the improper processing of waste, malfunctioning of the reactor, mechanical fatigue or ultimately the infeasibility of the technology for the application.

For a proper energy recovery sub-system, the production of non-condensable fractions would be of more interest to facilitate the product's (non-condensable and condensable fractions) combustion in the afterburner/atomiser. Researchers have reported many more constraints for the combustion of bio-oil in comparison to syngas, where the high-water content in the vapour phase has been found to reduce the energy density, the adiabatic flame temperature, local combustion temperature and combustion reaction rates [50]. In addition to the water content, the presence of solid particles (ash, etc.) and other physical properties could complicate the atomisation and lead to erosion in the pipeline. A previous study reported that sustainable combustion could not be achieved through bio-oil since the slight flash in the compound is suppressed by the evaporated water [75]. Furthermore, refractory behaviour observed with the long-chain molecular hydrocarbons complicates the thermal processing of them as well as the high oxygenate content leading to instability and higher viscosity [76]. Overall, through a novel chemical process design, the production of more syngas through pyrolysis followed by immediate energy recovery could provide the potential high temperatures for the ignition of bio-oil in the vapour phase. Some of the core parameters affecting the product distribution and properties will be discussed further to provide an insight on the optimum operating conditions of such a system.

To further elaborate, the term 'operational reliability' of such a system points out the production of a suitable gaseous fraction (both non-condensable and condensable) for rapid combustion and energy recovery. For syngas, as the focus of this study, delivering the highest reactivity for ignition and laminar flame speeds is vital for a reliable combustion performance in the after burner/atomiser. Research on the ignition and combustion properties of various blends of gaseous fuels indicate that the higher the H_2 content, the more O, H and OH radicals are released, enhancing the chain branching, propagation and termination reactions [77]. The presence of these radicals promotes the consumption of hydrogen, C_1 and C_2 – C_3 fractions and overall, the reaction rates which lead to lesser ignition delays of the fuel. Trials were conducted in high pressures where lower rates of radical production were observed at H_2/CH_4 concentrations of 40/60% [77].

Similarly, in a modelling study using Digital Analysis of Reactive System software (DARS), it was observed that the more CH_4/H_2 there is, the longer the ignition delay time, with the temperature playing a significant role where the change in reactivity was more sensible at lower temperatures [78]. Moreover, the laminar flame speed was reduced as the CH_4 with lower reactivity was increased in correlation with the reduction of H_2 .

Typically, another substantial fraction in syngas is carbon monoxide (CO), which results in the poor ignition of the fuel due to its low combustion rates. Analysis on the thermal efficiency of dual fuel operation of an engine shows that through an increase in the ratio of H_2/CO , an improved thermal efficiency was achieved [79]. However, this was limited to 75:25 as CO oxidation was optimum at this ratio. In addition, the higher H_2 content was observed to increase the flame travel and lower the auto-ignition temperature of the fuel.

Overall, a review of these papers reveals the improved combustion characteristics of syngas within an increase in the H_2 content. However, this would be at the cost of higher generation of NO_x fumes in the exhaust gas due to the presence of higher reactive radical species such as O and OH.

In the further steps, the effects of various consecutive process parameters specifying the evolution of different gas species will be discussed to select an optimum processing condition for such a system. Other than the combustion performance of the syngas, criteria to be considered in the further steps are:

1. Limiting energy consumption as much as possible.
2. Lesser chances of fatigue, particularly when the least maintenance is feasible.
3. Accommodating any incoming feedstock volumes with different physical characteristics.
4. Delivering emissions below regulating limits for both solid and gaseous by-products.
5. Reducing the solid waste volumes in considerable amounts.

2.3.3 Syngas Yield and Energy Content—A Trade-Off with Combustion Performance, Emissions and Bio-Oil Properties

2.3.3.1 Temperature vs. Yield

Numerous studies have investigated the effects of various process parameters on pyrolysis products. It is well known that the high heating temperature performs a dominant role on the yield and distribution of pyrolytic fractions [80] [81]. Higher temperatures provide sufficient energy for the bonds in biomass to break and achieve a better conversion efficiency [80]. Figure 2-3 illustrates the trends observed through the pyrolysis of various feedstocks in a few studies.

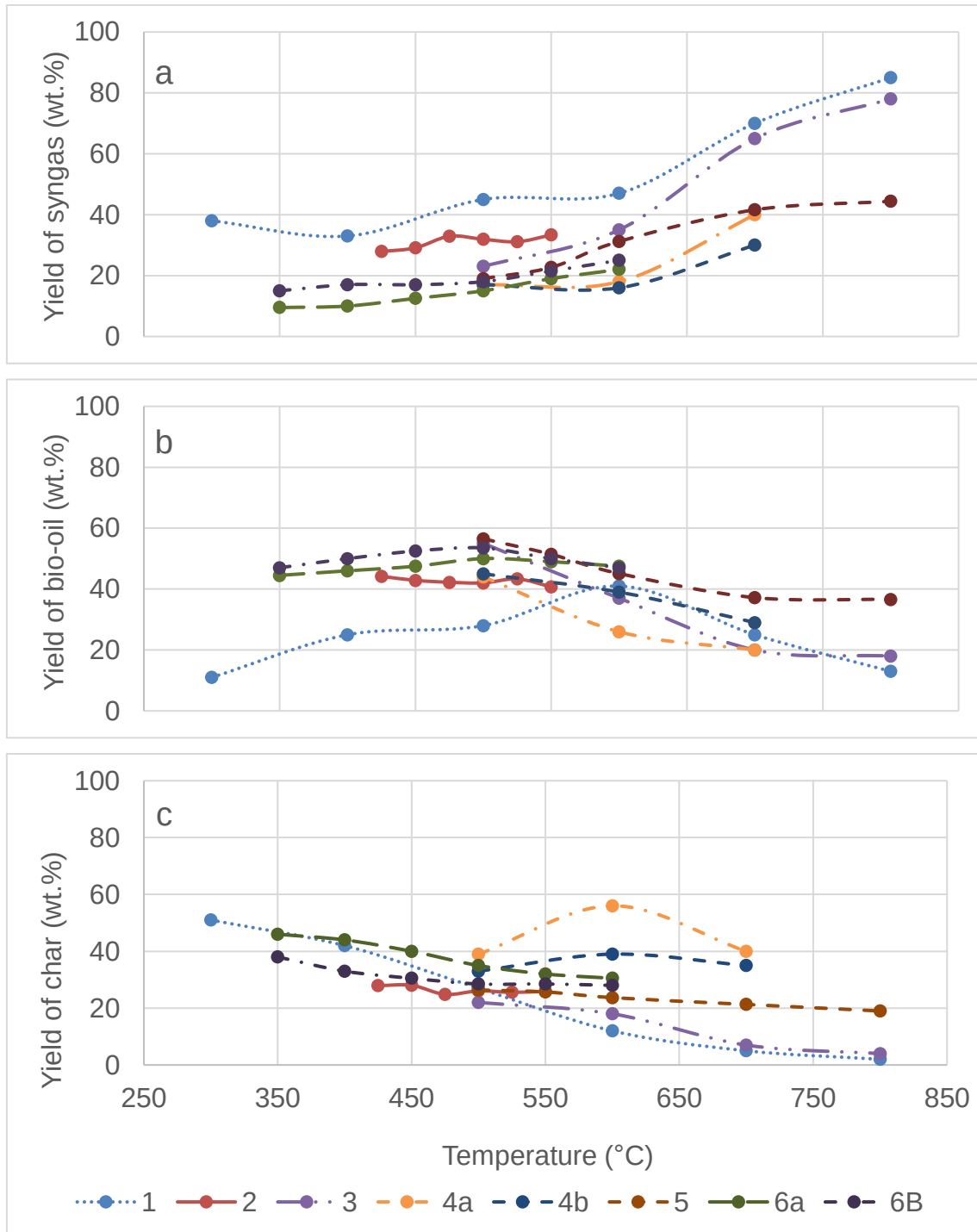


Figure 2-3 Effects of pyrolysis temperature on the yield of pyrolytic fractions: (a) non-condensable fraction, (b) condensable fraction, (c) residual char: (1) Anaerobically digested sewage sludge [82], (2) Milkweed [83], (3) Legume straw [84], (4a) Corn cob and (4b) Corn stalk [85], (5) Pine woodchips [86], (6a) Rice husk and (6b) Corn stalk [87].

Although the variety of feedstock compositions differentiates the yield of products, a common observation has been the increase in the yield of syngas at temperatures higher than 400 °C with drastic behaviour at 550 °C and further. In contrast, the yield of bio-oil follows the same trend after 400 °C but declines drastically at 500–600 °C and after. This shows the significant gas phase secondary reaction occurring at these temperatures, which is associated with the consistent decrease in the yield of char.

2.3.3.2 Heating Rate vs. Yield

Analysing the effects of heating rate on the yield, it is well known that the higher the heating rates (fast and flash pyrolysis), the more liquid oil could be produced through rapid extraction of the vapour [88]. However, research shows that for the syngas fraction, the heating rate plays a major role in the progressive generation of syngas during slow/intermediate pyrolysis limited approximately up to 200 °C/min [89]. Research on forestry residues shows that applying higher heating rates yields more syngas up to the point where heat and mass transfer limitations within the reaction area are overcome [90]. The product producer gas will be further discussed in later sections.

2.3.3.3 Temperature vs. Syngas Calorific Value

To suggest an optimum range of temperatures for such a system to operate at, the energy content of the syngas fraction should also be analysed. Figure 2-4 shows the calorific values (HHV) of the syngas obtained through temperature variations during the pyrolysis of various types of feedstocks in different reactor configurations and operating conditions.

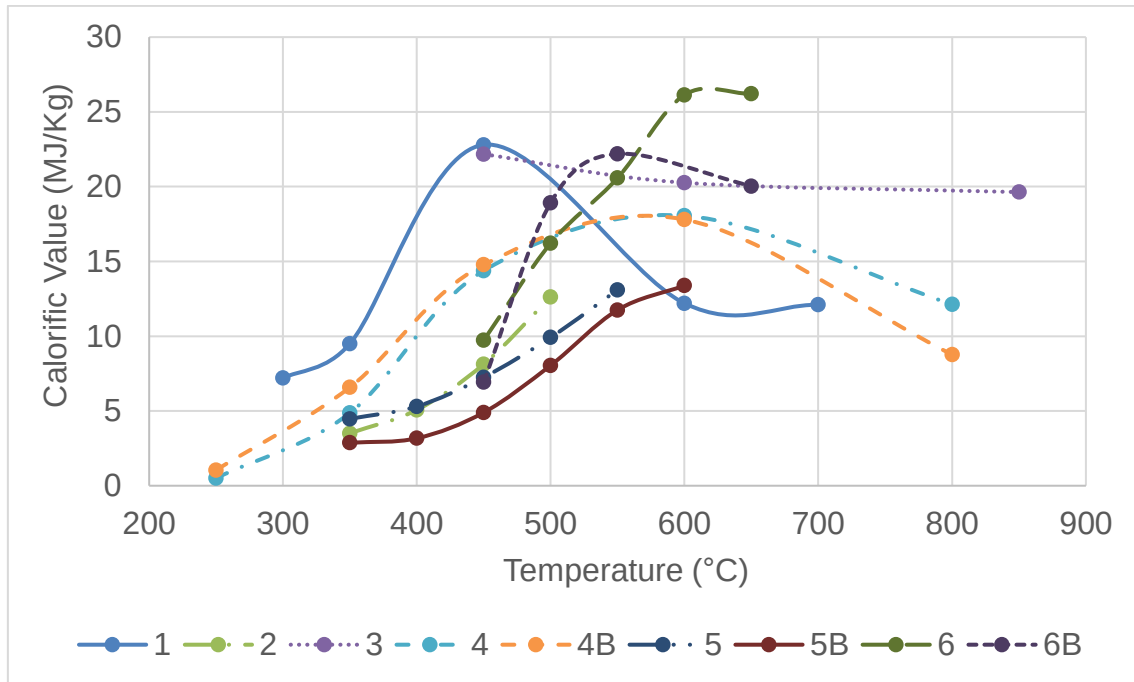


Figure 2-4 Effects of pyrolysis temperature on the calorific value (HHV) of the syngas: (1) Human faeces [57], (2) Sewage sludge [91], (3) Sewage sludge [5], (4 and 4B) Sewage sludge at 60 and 5 °C/min [92], (5 and 5B) Rice husk and corn stalk [87], (6 and 6B) Dried sewage sludge at 100 and 5 °C/min [93].

The theoretical calorific values in MJ/Kg were calculated using the data on the energy content of each gaseous species reported by NREL [94]. CO, CH₄, H₂, C₂ and C₃ were the only combustible species considered for the comparison commonly reported in all studies, while an average energy content of 65 MJ/Kg was assumed for the last two.

Typically, the most abundant species in the syngas fraction detected in various studies are mainly CO₂, CO, CH₄, C₂–C₃ and H₂ depending on the type of feedstock and process conditions. Clues from pyrolysis practices reveal evidence on the notable increase in the yield of CO and CH₄ at temperatures up to 600 °C and dominant H₂ at further temperatures [95] [96]. The production of more hydrogen can deliver zero carbon emissions upon the combustion of syngas, but the operating temperature should be considered carefully with regard to the

mechanical design of a system for sanitation where higher chances of fatigue are foreseen at higher temperatures in the structure of the reactor. Moreover, the higher yield of hydrogen leads to the conversion of primary tar from pyrolysis into polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene due to decarboxylation and dehydration [88] [95].

Highlighted in Figure 4, a temperature between 400 and 600°C during pyrolysis can trigger an upwards trajectory or a peak for syngas energy content for various waste materials. A reason for this is the generation of an energy-rich fraction such as C₂ at 450°C and maximum CH₄ up to 600°C [92]. Notably, the trends for the evolution of these gas species in this range of temperatures could be different based on the process conditions, feedstock compositions and reactor configurations [57] [97]. Furthermore, the progressive complex consecutive reactions for the generation of each species through pyrolysis and the consequent partial/complete gasification can be found elsewhere [96] [98] [99].

2.3.3.4 Heating Rate vs. Syngas Calorific Value

Analysis on the heating rate shows that the evolution of CH₄ and C₂–C₃ species increases through slow/intermediate pyrolysis, resulting in the peak calorific value at lower temperatures [93]. However, the concentration of these species stays almost constant at temperatures of about 450 °C and after [83] [86]. Focusing on the generation of energy-rich fractions such as CH₄ and C₂–C₃ fractions at temperatures ranging from 400–600 °C, Gao et al. [93] achieved a higher yield for these species through slow pyrolysis, whilst CO and H₂ evolution showed a peak through fast pyrolysis. In a study of chicken litter pyrolysis, the concentration of CO and H₂ increased at the expense of CH₄ and C₂ due to decarbonylation and steam reforming reactions through fast pyrolysis [89]. As discussed earlier, the increased yield of syngas in a range of heating rates limited between 0 and 200 °C/min could be attributed to the rapid decomposition of tar into gas, where a substantial increase in the concentration of CO and H₂ is observed [100].

2.3.3.5 Effects of Residence Time (RT)

Considering the residence time as another core parameter affecting pyrolytic product properties and distribution, an almost 50% breakdown of CO₂ is achieved through higher residence times in addition to the reverse impact of high heating temperature as a common observation in almost all studies on pyrolysis [101]. Moreover, prolonging residence times could generate a higher H₂ fraction through the following reaction:



Additionally, Jaramillo-Arango et al. (2016) suggested that enough residence times lead to thermodynamic equilibrium, resulting in H₂ overtaking CO₂ concentrations [82]. A review of multiple studies outlined significant changes in the yield of products achievable through RT variation. This is where the maximum liquid yield is obtained with a lower RT and rapid vapour extraction, whilst prolonging RT leads to the formation of syngas through secondary cracking; both are associated with char breakdown to different contents [102] [86]. However, the effects of RT are known to be insignificant on the overall syngas and liquid oil properties but are associated with a progressive decrease in the yield of char limited to the completion of reactions [103] [86].

2.3.3.6 Effects of Feedstock Flow Rate

The throughput of a system implemented for on-site sanitation is highly variable depending on the application, where a high/low frequency of toilet usage might lead to the system's malfunctioning due to a blockage, the improper conversion of waste materials or immature moisture handling within the processing timeframe. Results from an analysis on the feed flow rate show that depending on the design of the system, the vapour residence times start to decline as the flow rates increase, and consequently a higher bio-oil yield could be generated as the chances for secondary reactions diminish [104]. Detrimental impacts of this parameter in the case of improper design could be the accumulation of tar and particles in the downstream pipeline or a disruption in the operation of the afterburner. A similar phenomenon to the previous citation was observed in a

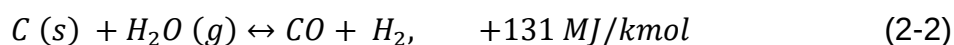
study on the pyrolysis of forestry waste, where insignificant impacts on the surface functionality of bio-oil were recorded [86]. Moreover, the hyphenation of the gas fraction showed that at a constant residence time of 5 min, the CO₂ concentration was decreased as the chances for primary decarboxylation in the reaction area decreased with higher flow rates.

2.3.3.7 Effects of Initial Moisture Content

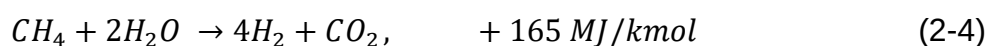
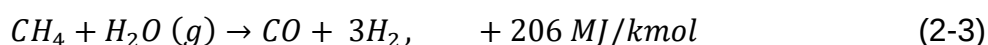
Moisture content has a direct impact on the maximum recoverable energy in such a system where excessive water contents could perform a thermally parasitic role during thermal conversion, which must be considered.

Results from multiple studies confirm that the generation of higher yields of syngas to the detriment of the yield of bio-oil was achieved in most of the cases [105] [84] [82]. This has been associated with the reduction of char in the system mainly when higher residence times (to conduct reforming) were applied during the process. The governing reactions occurring through the pyrolysis of wet waste materials leading to the partial gasification of organics are [63] [52]:

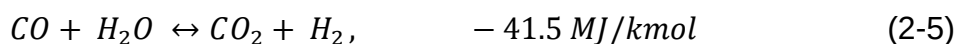
Steam gasification reaction:



Steam reforming reactions:



Water gas shift reaction:



Mei et al. (2020) observed that the steam-rich atmosphere within the reaction area enhanced water gas shift and steam reforming reactions. This resulted in the conversion of pyrolysis intermediate products (liquid oil) to hydrogen,

specifically with the catalytic effects of char at higher temperatures of 600 °C [106]. However, temperatures were found to have an insignificant effect on the yields of by-products below 700 °C [51]. This phenomenon was likely due to the difference in the composition of raw materials [52]. Because of the above equations, the concentrations of H₂ and CO₂ have shown elevation, while CH₄ and CO have decreased where the water gas shift reactions were dominant. Consequently, the calorific value of the gas fractions has declined due to the generation of more hydrogen with a lesser energy content compared to CH₄ and C₂ fractions, and so H₂/CO and H₂/CO₂ ratios increased gradually. Further analysis on bio-oil shows that a higher initial moisture content is conducive in the reduction of longer chain hydrocarbons with higher boiling points in the tar fraction (bio-oil) to form lower weight gas species [106]. However, the associated effects of temperature should be disregarded since the production of two or more ring aromatic PHAs is significantly affected at temperatures higher than 600 °C [51].

Finally, the pyrolysis of wet waste materials could enable higher chemical energy stored in the syngas through gasification reactions of the char and steam reforming of the oil [106]. However, an important factor to be considered is the energy recovery efficiency of syngas with alternative moisture contents. The authors observed the suppression of the total recoverable energy from the by-products due to the loss of sensible heat of the products and latent heat of residue steam vapour [106]. This study investigated the syngas properties within a separate reforming section where the authors demonstrated that a moisture content of 40% delivered the highest energy recovery efficiency of 44.18% from the syngas. The heat consumption for the evaporation of the water content, which does not take part in thermochemical reactions, was found as a possible reason for this.

2.4 Conclusion

This review followed two comprehensive objectives, further mentioned below, with an aim to address a suitable technology for the proper on-site conversion of solid waste materials generated in non-sewered applications:

- To provide an overview on the existing solid waste management/stabilisation methods and their associated implementation challenges in commercial/pilot, laboratory and small scales.
- To select the most promising method and further address the drawbacks.

Nonetheless, the primary aim for these applications is to reduce the waste volumes in sensible amounts and ensure the safe discharge of the products. Typically, the systems implemented for such applications must deal with limitations on regular maintenance and process control for the efficient conversion of sewage-type material in alternative volumes. These additional problems further complicate the design and optimisation of such a system.

Throughout this study, pyrolysis was observed as the most promising method among the existing technologies due to its lower emission rates in large scales and lesser operational challenges both in commercial and small scales. Lower heat fluxes within the reaction area enable the accommodation of alternative feedstocks with lesser necessary optimisation and enhances the handling of moisture content. A major technical challenge observed with this technology is the energy intensity in addition to the pre-treatment (drying), which was addressed through the addition of an on-site rapid energy recovery step from the by-products. A pyrolysis temperature of 400–600°C and the heating rates pursued at low ranks could result in a sustainable thermal conversion range for moist waste materials. These conditions would aim to produce the maximum yield of syngas with the highest calorific value, which facilitates the combustion performance of the vapour fuel in the afterburner/atomiser. Excessive heat upon the complete combustion of syngas and liquid fuel can potentially limit the energy consumption of pyrolysis or the inevitable drying stage in the system. This study does not take heat waste and ramp up steps into consideration. However, if the overall costs due to energy consumption or pre/post-treatment remain less than the current methods for management or disposal, this solution could be explored through further research. Using a novel design, the detrimental effects of particle size and alternative flow rates on both the conversion efficiency and operational performance could be alleviated through the maximisation of residence times and

fuel fluidisation. All of these would aim to produce the highest H₂ and C₁–C₃ fractions in such a range of temperatures while producing an energy-rich gaseous fraction for energy recovery.

For future studies, extensive research on the novel design, useful contents of moisture, potential emissions from such a system and ignition mechanisms of bio-oil in the vapour phase would be suggested.

2.5 Overall research gaps

A review of the available research on sludge management methods revealed a major gap in the utilisation of thermal treatment methods for mobile applications. In addition, small-scale implementation of such technologies still lack research on operational challenges, process efficiencies and emissions. On top of these, with respect to management of sludge in mobile applications (rolling stock), the chemical properties of the solid wastes generated from these sources are barely investigated. Meanwhile, no research has been conducted to explore the achievable products from the thermal processing of waste materials generated on trains to the best of our knowledge.

2.6 Thesis aim and objectives

The aim of this PhD project was to design and optimise an innovative thermal treatment system for the processing of human faecal sludge generated from the on-board train toilets. Such a system should be capable of providing a rapid processing timeframe for the solid wastes whilst ensuring a safe disposal of products would occur.

The project has the following objectives-

1. To conduct a critical literature review on the application of thermal processes in commercial and small scales to select a suitable technology for ClearTrack application. To identify the process constraints and discuss the requirements for technology implementation and how the challenges could be addressed.

2. To carry out the complete chemical and thermal characterisation of the faecal sludge generated in on-board toilets to understand the properties of the feedstock as well as their kinetic behaviour.
3. To develop a novel drying unit for the reduction in moisture and volume of sludge prior to final stabilisation as well as nutrient recovery.
4. To design and evaluate the thermochemical process of an innovative pyrolysis reactor.

Specific hypotheses are described for each individual Chapter, however at an early stage of the PhD project the following hypotheses were formulated:

“Thermal treatment technologies are adoptable to mobile applications for the proper management of sanitary wastes”.

“Small-scale pyrolysis systems are robust methods for value recovery from non-sewered faecal sludge through combustion or off-grid utilisation of products”.

“Pyrolysis technologies are able to convert solid fuels with alternative physiochemical properties needing lesser control and automation in comparison to gasification and combustion”

Chapter Three

3 Thermochemical Characterisation and Pyrolysis Kinetics of Human Faecal Sludge (HFS)

This Chapter covers the thermochemical characterisation of the faecal waste generated in on-board train toilet. This is followed by an analysis on the pyrolysis conversion of HFS from trains to determine their kinetic properties, e.g., activation energies (E) and frequency factors (k_0). The data obtained in this Chapter facilitate the technology development and further pave the way for future research in prediction models for such technologies.

Abstract

Extensive program of analysis on the non-sewered human faecal sludge (HFS) generated in on-board train toilets is carried out to determine their chemical and energy properties. The analysis on the ultimate and proximate characteristics of the solid wastes confirmed the high moisture contents (~90 wt.%) alongside their lower ash contents (>10 wt.%) in comparison to municipal sewage sludge samples in other research projects. Considerable number of tests on the thermal decomposition properties of the faecal sludge as well as toilet papers used on trains revealed their similarity in nature with the decompositions occurring in two steps. Maximum degradation temperatures of the faecal sludge improvised around 366°C. The activation energies of the reaction occurring during the pyrolysis of faecal sludge (FS) improvised between 185 – 220 kJ/mol through the entire conversion rates. The provided data in this study are useful for the development of prediction models for thermochemical processes implemented for non-sewered sanitary applications and vital for the R&D of such technologies.

3.1 Introduction

It is important to understand the energy and chemical properties of the waste prior to the design of a thermal treatment system. In addition, analysis on the pyrolytic conversion of the waste can contribute further information on the constituents of the waste needing cracking and break-down, all of which are elaborated in this Chapter.

Thermochemical conversion processes have recently gained attraction for the simultaneous on-site sanitation and energy recovery from human faecal sludge regarding their high energy-content as 24 MJ/kg [107]. Indeed, thermochemical conversion processes are capable of providing a more rapid processing timeframe comparing to anaerobic digestion technologies. This approach promotes faecal sludge management in low-income countries or parts of developed countries where sewage infrastructure is difficult to be accessed [108]. For instance, reliability issues involved with on-board train toilets could be pointed out where a controlled emission tank (CET) is used for the storage of sewage generated on trains and further emptied in depots using extraction infrastructure [3].

The fundamental concepts in the thermal conversion of human faecal waste through combustion and gasification has already been extensively investigated in the past [107] [109] [110]. In addition, the implementation of such technologies in small scales were researched [108]. Our critical review of the research completed in this field has revealed the overall challenges associated with thermal processes, suggesting pyrolysis for future research [6]. This research is completed as a part of ClearTrack initiative, a collaboration between Cranfield University and GBR-Rail Ltd. in 2019, which investigates the implementation of a decentralised wastewater treatment system for use in railway rolling stock. ClearTrack system is comprised of a water purification and recovery loop as well as a solid waste management system. The solid processing system pursues the stabilisation of the waste using a drying unit for the pre-treatment of the sludge

integrated with a pyrolysis reactor, for the final processing of the hazardous waste.

Pyrolysis, the thermal disintegration of the organic matter in anoxic conditions, deliver energy-rich products that are commonly known as syngas, bio-oil and the pyrolytic char [111]. The process involves dominant endothermic sequential reactions with an enthalpy ranging from 0.7-8.6 MJ/kg depending on the type of feedstock, operating conditions and heavily on the fuel's moisture content [112] [113]. However, evidence for the exothermicity of the human faeces pyrolysis are available [114], and results from other studies confirm an economically feasible pyrolysis process through the combustion of products and energy recovery [115] [116] [117].

This study investigates the chemical properties and kinetics of the pyrolysis of heterogenous faecal sludge generated in rolling stock for the first time. Exploration of kinetics is commonly reported essential for the design and development of pyrolysis reactors [118]. The combination of the data on the activation energies, frequency factors and reaction mechanisms together with the heat and mass transfer models enable the production of more accurate prediction models facilitating industrial biomass and waste utilisation. Herein, the complex decomposition reactions of solid wastes are studied with thermogravimetric analysis, a technique for simultaneous measurement of temperature and weight loss [119]. Among the plethora of kinetic models available in literature [120] [121] [122], distributed activation energy model (DAEM) was used since it has been identified a mature and versatile approach for the prediction of unknown parallel complex decomposition reactions through biomass pyrolysis [123] [124].

3.2 Materials and methods

3.2.1 Feedstock preparation

Typically, the physiochemical characteristics of the sanitary wastes generated on different trains is different due to its heterogeneity and heavily depends on the type of train. This stems in the fact that the passenger's behavioural pattern

differs meaning that the chance of defecation is higher on long-journey (inter-city) trains and alternatively lower on commuter trains. This could lead to a waste stream consisting alternative ratios of human faecal matter, paper tissue and foreign objects (e.g., menstrual products) that is neglected here. Hence, characterisation of the waste generated from different trains is necessary to obtain an insight on the potential types of the waste streams that could enter the solid waste thermal treatment system. The replenishment of the water tanks and emptying of the CETs are completed when the trains are called for refuelling at the depots for which the frequency is known to be different according to the type of the train and the distance it travels. Hence, it was tried to extract the samples from the CETs on the trains that had the more rapid depot-visit frequency to reduce the chance of biodegradation. Waste/black water from the CET was sieved with a 1mm mesh after extraction and the resultant faecal sludge, shown in Figure 3-1, underwent chemical characterisation under the Cranfield University Research Ethics Scheme, CURES/9346/2019 and CURES/7933/2019. During the characterisation stage, the raw faecal sludge was stored in a fridge at 4°C to minimise the rate of microbial degradation.

3.2.2 Chemical characterization

Samples were thawed at room temperature and proximate analysis was conducted using the methods outlined in BS EN ISO 18134-2, BS EN 14775 and BS EN 15148. Conducting the experiments, the final content of moisture, ash and the volatile matter were calculated with the following equations:

Moisture content

$$M_{ad} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \quad (3-1)$$

Ash content

$$A_d = \frac{(m_{a3} - m_{a1})}{(m_{a2} - m_{a1})} \times 100 \times \frac{100}{100 - M_{ad}} \quad (3-2)$$

Volatile matter

$$V_d = \left(\frac{100(m_{v2} - m_{v3})}{m_{v2} - m_{v1}} - M_{ad} \right) \times \left(\frac{100}{100 - M_{ad}} \right) \quad (3-3)$$

M_{ad} , A_d and V_d are the contents of moisture, ash and volatile matter among the moisture figure is on as received basis while the rest of on dry basis. m_1 , m_{a1} and m_{v1} are the masses of empty crucible. m_2 , m_{a2} and m_{v2} are the masses of test portion plus crucible before heating. Nomenclatures m_3 , m_{a3} and m_{v3} are the masses of crucible plus solid residue after heating in each experiment. The fixed carbon content was calculated by the subtraction of the dry wt.% percent of ash and volatile from 100%.



Figure 3-1 Faecal sludge obtained from sieving the waste/black water collected from CET

Additionally, using the method described in BS EN 15104, the ultimate composition of C, N and H of the samples were determined using an elemental analyser. Following this, the oxygen content was determined by subtracting the wt.% of carbon, nitrogen, hydrogen and ash from 100%. Furthermore, using the bomb calorimetry method outlined in BS EN ISO 18125, the calorific value (HHV) of the dried samples were measured. The washings from bomb calorimeter were

analysed via ion-chromatography (Dionex ICS-1600) for the content of sulphur and chlorine as elaborated in BS EN ISO 10304. Measuring the content of sulphate and chloride anions, the real concentrations of aforementioned inorganics were calculated as following:

$$Real\ Chlorine = \frac{Chloride \times dilution\ factor \times M_r * \frac{1L}{1000mL} \times V_W}{M_S} \quad (3-4)$$

$$Real\ Sulphur = \frac{Sulphate \times dilution\ factor \times M_r * \frac{1L}{1000mL} \times V_W}{M_S} \quad (3-5)$$

In which, M_r is the stoichiometric relative molar masses of inorganic to its anion, V_W is the washing's volume and M_S represent the mass of sample combusted within the calorimeter.

3.2.3 Pyrolysis experiments

The faecal sludge samples from two trains as well as the tissue paper used on-board were dried to a constant weight and grounded due to bulky structure of tissue paper to obtain a better mixture for thermal decomposition analysis. The pyrolysis tests were performed in a TGA8000 from PerkinElmer and the un-subtracted weight as well as sample temperature were recorded through time. During each experiment <10 mg of the dried faecal waste was weighed into a carousel which was then loaded into the furnace. Experiments were performed under 60 mL/min of nitrogen flow to ensure proper pyrolysis while mitigating any secondary reactions. The program for the TG analysis of faecal sludge samples was as follows: heat up from 50°C to 105°C at a rate of 50°C and hold isothermal for 20 minutes to remove any moisture within samples, temperature scan from 105°C to 700°C at a desired heating rate and hold for 10 minutes followed by cooling down. The heating rates used for the pyrolysis stage of program for one batch of faecal waste (FS1) was 25, 50, 75 and 100°C/min while another batch of sample (FS2) and the tissue papers used on train (TT) underwent 10, 20, 30, 40°C/min to cover slow – intermediate pyrolysis ranges.

3.2.4 Estimating kinetic parameters using DAEM – Theory

The fundamentals of distributed activation energy model were originally proposed by Vand [125], which has been used to study the volatile conversion kinetics of various fossil and biomass fuels [126] [127]. The DAEM model assumes the simultaneous occurrence of an infinite number of irreversible first-order parallel reactions that have a range of activation energies, leading to the decomposition of complex biomass. Following this, a continuous distribution function $f(E)$ is then used to represent the range of activation energies possessing the same frequency factor k_0 at the same conversion rate [119] [128]. Miura et al. (1998) presented an integral and a differential method for DAEM among which the former one proved to be more accurate [129]. In this model, the change in the total volatiles (V) correlated with the mass fraction at time (t) or temperature (T) is defined through the following equation:

$$1 - \frac{V}{V^*} = \int_0^\infty \exp\left(k_0 \int_0^t e^{-\frac{E}{RT} dt}\right) f(E) dE \quad (3-6)$$

In which, V is the volatile content at temperature T , V^* is the effective volatile matter in experiment ($\alpha = V/V^*$), k_0 is the frequency factor to the corresponding E value. The variables inside Eq. (3-6) were evaluated defining a function $\phi(E, T)$ that changes sharply with activation energy at a given temperature which is approximated by a step function (U) at an activation energy $E=E_s$ at the selected temperature T . The equation was further simplified to:

$$\frac{V}{V^*} = 1 - \int_{E_s}^\infty f(E) dE = \int_0^{E_s} f(E) dE \quad (3-7)$$

The selection of activation energies E_s was to satisfy $\phi(E, T) = 0.58$. Further approximations described the Arrhenius equation from which the slope and intercept represent E and K_0 respectively [130].

$$\ln\left(\frac{\beta}{T^2}\right) = \ln\left(\frac{k_0 R}{E}\right) + 0.6075 - \frac{E}{RT} \quad (3-8)$$

β represents the heating rate and R is the universal gas constant.

3.3 Result and discussion

3.3.1 Energy and chemical properties of waste

Chemical properties of waste in CET from different types of trains are presented in Table 3-1.

Table 3-1 Chemical characterisation of faecal sludge as well as toilet paper used on trains

	CET	1	2	3	4	Train Tissue
Proximate % (Dry basis)	Mc ¹ (arb%)	91	90	93	92	6.5
	Ash	5	4	7	6	2
	V _M ²	83	82	83	81	89.5
	F _C ³	12	13	10	13	8.5
Ultimate % (Dry basis)	C	44	42	46	43	42
	H	7	7	8	7	5
	N	1	1	2	1	0
	O	43	46	37	43	51
ppm	S	960	--	0	0	--
	Cl	3450	--	3511	5226	--
Calorific value	Dry basis (MJ/kg)	18	19	17	17	17

Similarity of the waste and toilet paper in composition reveals low frequency of defecation on trains from which samples were collected from, leading to a lower calorific value due to higher oxygen contents in comparison to homogenous faecal matter feedstock [109] [130].

¹ Mc arb: Moisture content – as received basis

² V_M: Volatile matter

³ F_C: Fixed carbon

3.3.2 Thermogravimetric analysis

The data on the weight loss of sample in TG analysis were normalized on the following basis:

$$M = \frac{(W_t - W_f)}{(W_i - W_f)} \quad (3-9)$$

In which, W_t is the mass of sample at time t , W_f is the mass of final residue and W_i is the initial mass of sample.

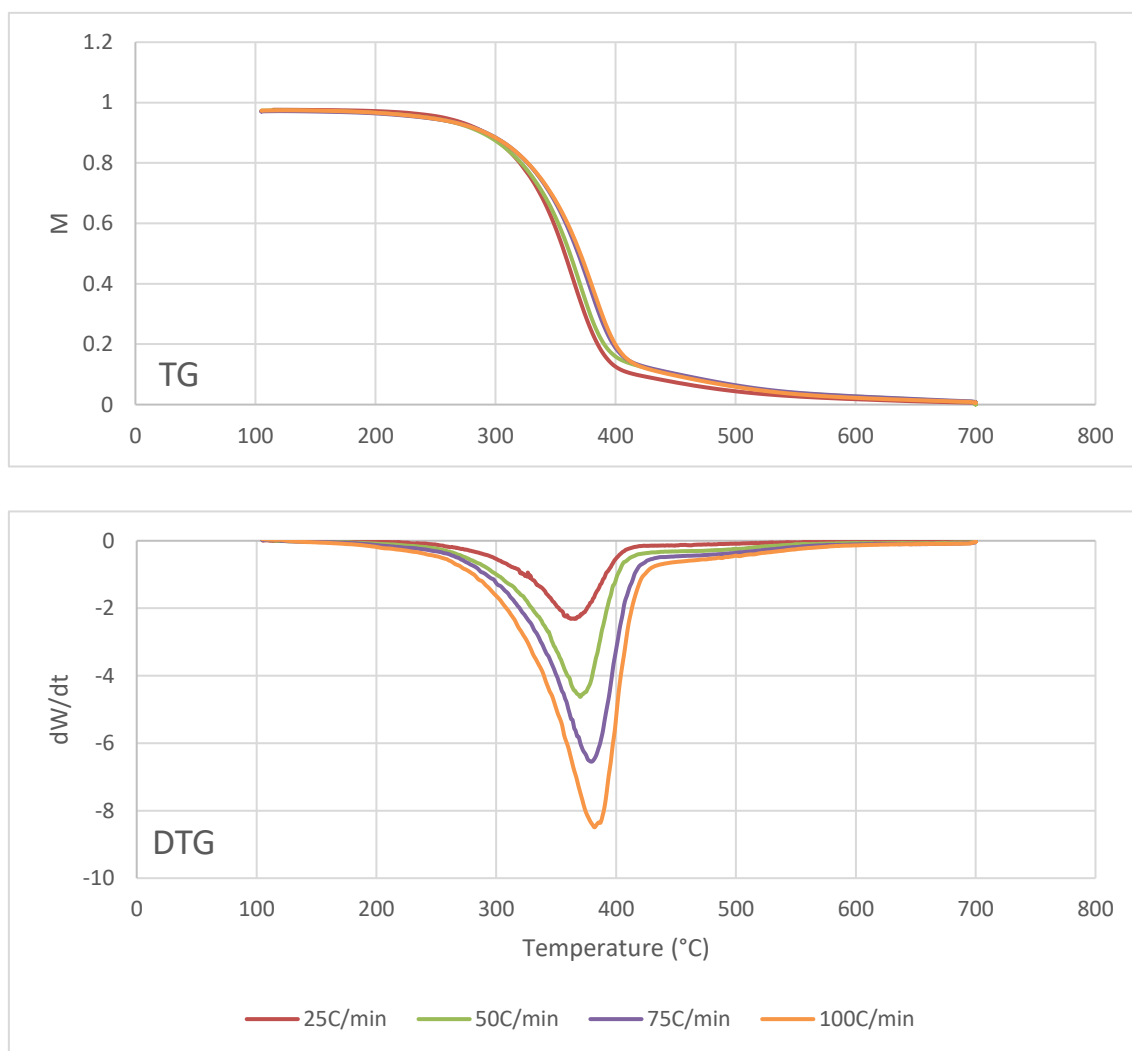


Figure 3-2 TG and DTG curve of faecal sludge undergoing intermediate pyrolysis

A similar conversion was observed for each sample at different heating rates. For simplicity in discussion, thermal gravimetric curve and its differential version (DTG) for the pyrolysis stage of samples (105 – 700°C) heated under intermediate conditions (FS1) are depicted in Figure 3-2. Results showed almost 90% mass loss of samples up to a temperature of 500°C.

Analysis on heating rates of 25 °C/min up to a maximum temperature of 700°C revealed the peak thermal degradation (DTG) at 366°C while this figure shifted to a higher temperature 382°C for 100°C/min heating rates similar to findings in another study on the pyrolysis of human faeces [131]. Unlike other studies on the kinetic analysis of sewage sludge and human waste [130] [132] [133], degradation of faecal sludge collected from CET took place in two steps similar to a study on pyrolysis kinetic study of various papers including tissue paper [134], ranging nearly from 200 – 400°C and 400 – 500°C. The approximate peak between 200 – 400°C is typically attributed to the decomposition of cellulose, hemicellulose [128]. Another minor trough was observed between 400 – 500°C. Barneto et al. (2009) observed the major conversion of non-biodegradable organic matter of sewage sludge occurring between 400-550°C while the biodegradable fraction was decomposed from 150 – 400°C [135].

3.3.3 Kinetic analysis (E, k_0)

Figure 3-3 shows the linear and parallel developments for the samples pyrolyzed at different heating rates, within a conversion rate ranging from 0.1 – 0.9. The Arrhenius plots of $\ln(\beta/T^2)$ vs. $1/T$ suggest the simple description of faecal sludge pyrolysis with a set of similar first-order reactions.

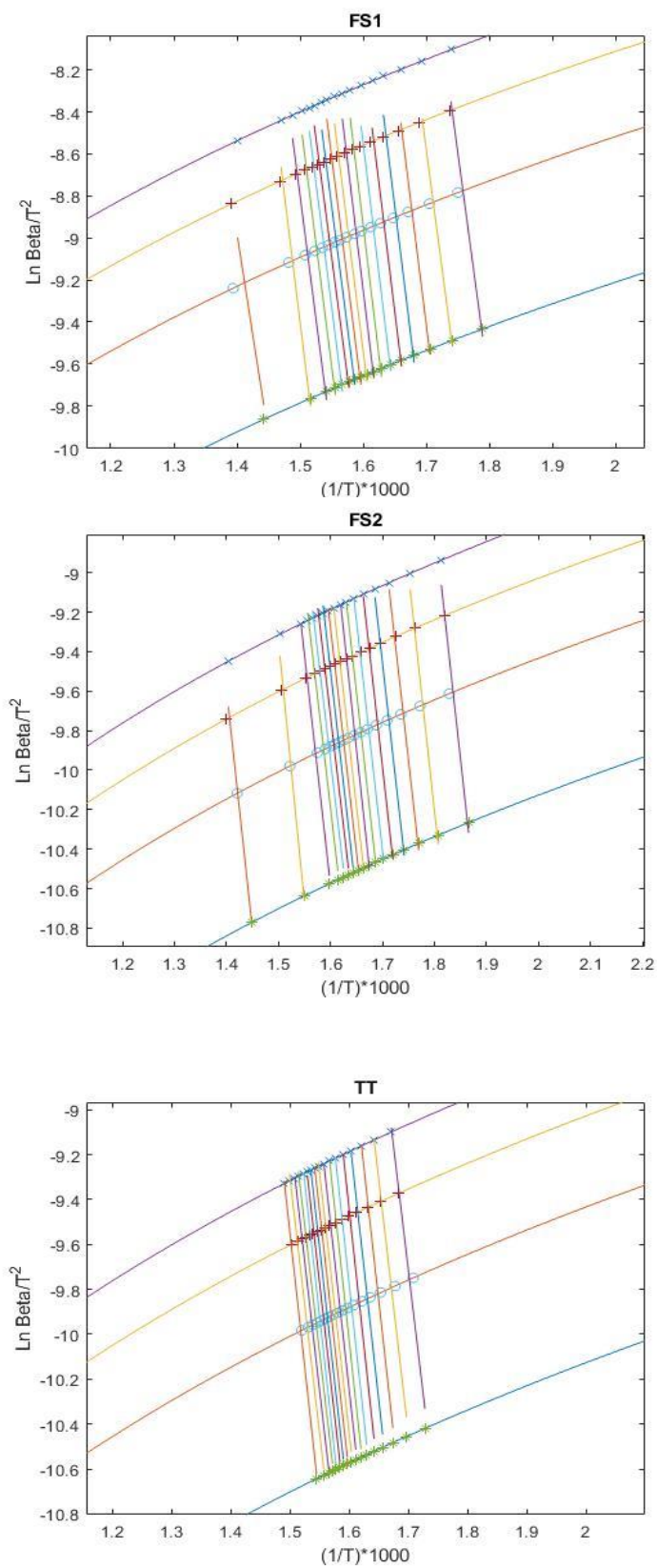


Figure 3-3 Arrhenius plots using the TGA data of FS1, FS2 and TT

Using Eq. (3-8), the values of activation energies and frequency factor (k_0) were determined from the plots of Arrhenius. High values of R^2 resulted from these analyses confirmed the validity of the model for the description of faecal sludge kinetics. Together with the correlation factors, the calculated activation energies for the conversion values of 0.1 – 0.9 are illustrated in Figure 3-4. The activation energies for FS1 improvised between 185 – 206 kJ/mol for conversion values ranging from 0.1 – 0.85 while R^2 remained ≥ 0.9 .

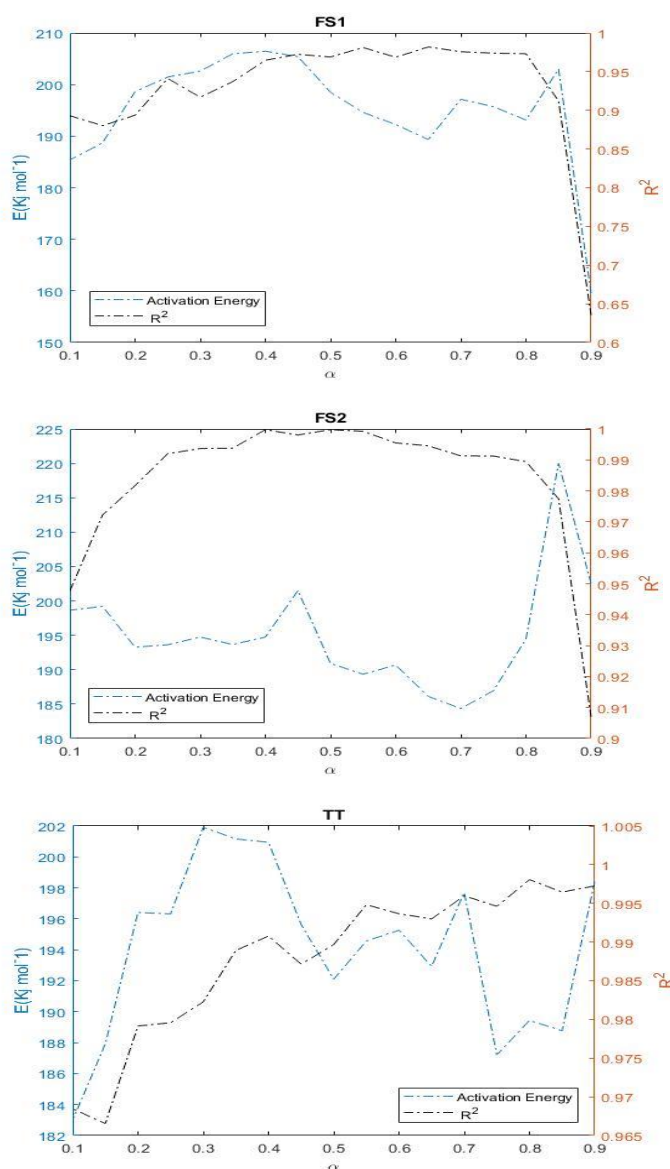


Figure 3-4 Activation energies and correlation factors vs. conversion rates

Analysis on the pyrolysis kinetics of FS2 revealed R^2 values higher than 0.9 until a conversion value of 0.9 with the activation energies varying between 186 – 220 kJ/mol. In a study on the kinetics of blended sewage sludge with pine sawdust (PS) pyrolysis using DAEM, the model was found unsuitable for the prediction of blends with 75% and 50% of PS above conversion values of 0.8, due to the altered sequence of temperature for the same degrees of conversion [136]. Hence, the lines towards the end of conversion ranges shown in Arrhenius plots tend to cross each other and should be neglected in the analysis. Meanwhile, the surge in activation energy for FS2 between 0.8 and 0.85 conversion values might be due to elementary steps not being captured by the model [130]. Overall, the determined activation energies for the faecal waste samples and the toilet paper used on train fell within the ranges reported for sewage sludge and faeces remaining closer to that of paper [136] [130] [134].

The values of frequency factors (k_0) were also determined from Eq. (3-8) and are provided in Appendix C. The k_0 values for the conversion ranges of 0.1 – 0.9 for FS1, FS2 and TT ranged from 10^{12} to 10^{14} , 10^{11} to 10^{15} and 10^{11} to 10^{13} , respectively.

3.4 Conclusion

Different batches of human faecal sludge generated in on-board train toilet underwent an extensive program of chemical characterisation throughout this chapter. The analysis on the proximate properties of the waste showed the high contents of water (~90 wt.%) and volatile matter (~80 wt.% dry basis) in the solid feedstock requiring treatment. The ultimate properties of the solid waste confirmed the abundance of carbon and oxygen in their structure resulting in calorific values lesser than 20 MJ/kg. Furthermore, the inorganic contaminants analysed through ion chromatography of the dried waste highlighted the alternative contents of chlorine and sulphur due to the difference of waste chemical natures. The acquired data are extremely helpful for the design and optimisation of a negative emission thermochemical process in the context of a wastewater treatment system. However, investigation of the physiochemical

properties of the wastes in other trains with different journeys are crucial for future research to evaluate the differences of waste streams.

The comprehensive thermogravimetric study supplied valuable insights into the nature of organic structures within the sewage wastes and the toilet papers used on trains. The samples decomposed with a maximum rate at temperatures about 366°C.

Analysis on the kinetic properties of the reactions occurring through the pyrolysis of faecal sludge were studied using the commonly utilised distributed activation energy model (DAEM). The results confirmed the description of the reactions occurring through the pyrolysis of faecal sludge and paper materials use don trains with a set of first-order irreversible reactions.

Further research on the prediction of conversion ranges (V/V^*) through solving the values for distributed activation energy function, $f(E)$, with the supplied mathematical equation is necessary for further model validation. In addition, investigation of other kinetics methods enables accurate kinetic parameters, all of which are key parameters for the development of prediction models and simulation of pyrolysis technologies.

Chapter Four

4 Development and Evaluation of a Single Screw Drying Technology

This Chapter demonstrates the development of the single screw thermal drying unit for the pre-treatment of faecal sludge feedstock. Furthermore, the testing steps will be elaborated followed by the discussion of the effects of process parameters considering operational constraints for further use in Chapter 5.

Abstract

A novel thermal screw drying system for the batch processing of human faecal sludge (HFS) in rolling stock is designed and the effects of process conditions such as high heating temperature, residence time and feed flowrate on moisture, nutrients and other inorganics are explored. 40% reduction in moisture was achieved while a consistent and robust operation of the unit was ensured at temperatures of 150°C with almost 60 minutes of residence time. Prolonged residence times enabled a further 25% reduction in moisture at the cost of ineffective sludge fluidisation resulting in impersistent drying efficiencies. Operating temperature played a dominant role over residence time for flushing the nutrients in the dryer's condensates with the ammonium (NH_4^+) representing the most abundant N-compound (~1200mg/L). Overall, the carbon emissions from HFS remained negligible through conductive drying at temperatures up to 150°C. Implications for future design modifications are provided throughout the study.

4.1 Introduction

Sewage solid waste is a heterogeneous mixture of faecal organic substances, inorganic impurities, and high moisture content of up to 98% [137], which pose a threat to the environment in case of improper disposal. Conventional stabilisation methods practiced in wastewater treatment plants for sewage wastes include digestion, dewatering and drying followed by landfilling for the final disposal, mostly facing issues such as improper conversion and intensive energy demand [138]. In the past decade, utilisation of thermochemical methods for the conversion of these feedstock materials have increased because of their high energy content ~ 22 MJ/Kg [139]. Despite the vast literature on the energy and resource recovery from sewage waste through thermal treatment in commercial applications, the on-site treatment of this waste in small-scales has gained attention recently to address challenges observed with sanitation in low-income countries [108] [130] [109] [140].

Commonly reported, utilisation of thermal treatment methods require fuel with much lesser water content to that of anaerobic digestion (as received feedstock) [139]. As a result, an inevitable drying step is planned for the pre-treatment of the feedstock almost taking 2260 kJ of unrecoverable energy for every 1 kilogram of water [141]. The moisture content present in the feedstock plays a key role in the physiochemical properties and energy content of the products from these treatment methods. In addition, operational challenges such as improper ignition and conversion of the fuel are raised when moisture content in the fuel exceeds limits of the application [109]. Hence, a variety of moisture content limits are reported depending on the treatment mode, desired product from the process, reactor design and processing conditions [6]. This ranges from $<50\%$ for combustion to $<10\%$ water content in the fast pyrolysis of sewage waste for the production of high quality liquid bio-oil [142] [143] [139].

The presence of moisture in the sewage waste occurs in two forms, namely unbound/free and bound water content. For the separation of unbound water content, dewatering mechanisms has been used to limit energy consumptions of

drying, which in best-case scenarios deliver products with 65-75% moisture content [144]. The interstitial/capillary, surface and the chemically bound water content, in turn has to be removed via drying at 105°C – 200°C considering the rate of volatiles driven off of the samples [145] [146] [147].

This study aims for the design and optimisation of a novel small-scale dryer for the on-site pre-treatment of sewage waste in sanitary applications. This research is conducted as a part of 'ClearTrack' initiative, a collaborative project between GBR-Rail Ltd. and Cranfield University, looking for the implementation of an on-board wastewater treatment system for trains. The system includes a solid waste and an effluent treatment and recovery loop to be retrofitted with the controlled emission tank (CET) which has been used to store sewage waste for further disposal using extraction pumps in depots [3]. The thermal treatment of solids takes place through pyrolysis for the production of the highest yield and energy content of syngas for combustion and energy recovery. Meanwhile, the liquid purification system aims to trap the contaminants through filtration mechanisms. Research in this field is very scarce to the best of our knowledge and this work extensively contributes to the knowledge on drying efficiencies and challenges observed with the constraints and physiochemical characteristics of such applications and waste materials respectively.

Overall, the objectives of this study are to conduct a review on the existing drying technologies to aid in the selection of a suitable technology for fast prototyping. In the next steps, the constraints associated with the design and application will be tested to optimise the dryer delivering suitable materials for further processing through pyrolysis. Meanwhile, the operational challenges with the drying of the waste will be highlighted.

4.1.1 Constraints and assumptions

Primary assumptions considered the presence of only faecal matter, Urine and tissue paper in the feedstock. Based on the overall system design, the waste to be fed into the dryer, passes through a dewatering unit, which separates the solid-

liquid effluent using a mesh. Hence, the feedstock's moisture content was determined after sieving with a mesh of 1mm pore size.

A key constraint in these applications is the frequency and volume of the solid waste entering the system. Different figures have been reported as the median daily weight of waste per defecation in various studies shown in Table 4-1. In addition, field research on trains and mobile applications also indicates the average frequency of defecation for the passengers. Hereby, an average solid volume of 160g for each person in addition to 16g of tissue papers (arbitrary) per defecation is assumed for a primary mass balance within the system. To predict the worst-case scenario for the volume of the feedstock entering the system, a safety factor of 2 is considered for each parameter. It is trivial that the assumption of safety factor for the number of defecations per day will increase the feedstock mass within the system as well. However, this is different to the mass of feedstock per defecation, multiplication of which by the safety factor affects the moisture reduction efficiency of the dryer running in batch mode. Considering the safety factor for all parameters, the overall figure for the feedstock mass stream was calculated as ~11kg/day.

Table 4-1 Primary mass flow assumptions for design

Reference	Average weight (g)	Frequency/day
[148]	35-796	--
[149]	128	--
[150]	250 (adult men), 111.3 (adult women)	--
[3]	106	16
Final assumption (safety factor of 2)	160g/defecation 16g of tissue	16
~11 kg / one day of train operation		

The overall operational mechanism of the system is based on providing batch inputs to the dryer accommodating individual's worth of solid volumes in a specific timeframe. Following this, the dried waste is stored in a chamber for further feeding into the pyrolysis reactor. Collection of waste from trains in the depot were limited and upon collection, the low content of solids in the CET showed the significant dependency of their volume on the type of train in terms of their journey and number of stops along.

Constraints on the retrofitting of the system for train also considers a length limited to <1000mm for the units and a height lesser than 5000mm, including the overall assembly and instrumentation. The system should be designed with the simplest configuration, for attachment to a pressurized toilet while air compression could be supplied to facilitate the system if needed.

Lastly, no auxiliary fuel or carrier gases can be supplied for the system and the processing temperatures should stand as low as possible in the 'ClearTrack' system.

4.1.2 Review of the existing drying technologies

The energy intensive process of water evaporation for the fuel pre-treatment, takes up almost up to 20% of the total industrial energy consumption [151]. Concerns with the energy intensity has constantly been raised for which various solutions such as reduction in evaporation load, increasing dryer's efficiency and improvement in the heat supply system was proposed [151]. Through drying of sewage waste material, various stages of physical properties such as wet (70-80 Mc%), pitting (60-65 Mc%) and granular (20-25 Mc%) occur. The plethora of drying technologies practiced in various applications are mainly fry-drying, bio-drying and air drying categorized into conductive, convective, and radiative modes depending on the heat propagation mechanisms [152]. Conductive drying implies the indirect heating of the feed using almost 10% of that air used in convective units for direct drying solely to remove the water vapour and mitigate the chance of moisture re-adsorption [153]. The radiative mode demands the use of carrier gas to purge vapour out and operates in penetrating (i.e., dielectric drying) and non-penetrating modes (i.e., microwave).

For the selection of a drying technology, constraints associated with application, drying time, process intensity and feedstock nature should be carefully considered. Various studies highlight the complexity of this task leading to unsuccessful practices even noting empirical considerations in their design [154]. Some of the existing technologies for direct and indirect air dryers are summarised in Table 4-2.

Table 4-2 Various air-drying technologies [147]

Convection (Direct)	Conduction (Indirect)
Rotary-drum	Thin film
Flash	Rotary-disc
Moving belt	Rotary tray
Centri-dryer	Screw conveyors

Typically, the waste material is exposed to very high temperatures in convection methods resulting in the production of gases. Moreover, in the case of sewage waste in small scale sanitary applications, convection methods could pose biological hazard in longer timeframes if air ingress occurs within the dryer. Indirect drying needs the heat to be transferred from a hot surface to the waste leaving this method with specific challenges. Unlike convection mode, the presence of no air or medium with high flow for the disintegration of wet waste/sludge has been observed to raise problems, particularly due to their sticky nature (solid content of 55-70%) and lead to fouling of the hot surface. As a solution, various innovative designs for the agitation and scraping of the sticky waste has been investigated [152] [147].

4.2 Methods

4.2.1 Design of the dryer

For this application, a conductive single screw drying unit was manufactured by GBR-Rail Ltd., depicted in Figure 4-1. Through this stage literature on the design [155], screw conveyor engineering brochures and manufacturing experts were consulted. The screw has an outer diameter (OD) of 68.5mm welded on a hollow shaft with 17.5mm OD to enable the chance of energy recovery. Despite the variety of screw shapes, a normal flight was selected for its simplicity during manufacturing process. The clearance between screw and shell was kept at minimum (~3.5mm) while the pitch remained equal to screw OD common in screw conveyors. All parts of the unit were manufactured with stainless steel 316.

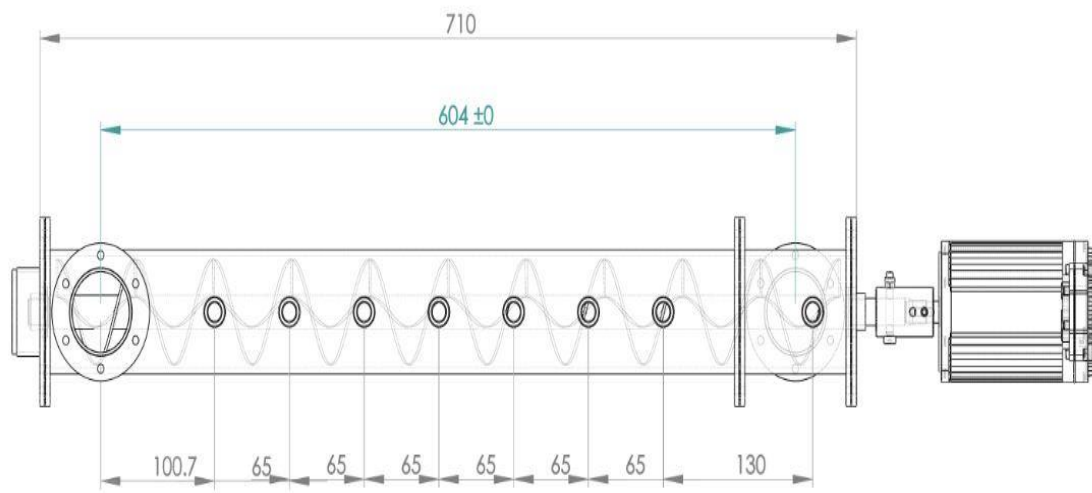


Figure 4-1 Dryer sizing schematic

The overall length of the unit including the motor assembly adds up to 950mm, built in a modular form with the vapour exit ports shared along the length of the tube. Stainless steel pipes were connected to the vapour exit ports, extracting the vapour through suction pressure generated by a vacuum generator from Air engineering controls Ltd. having a diameter of 19.1mm operating with compressed air at 3.5 bar. The implemented vacuum generator facilitates the extraction of vapour to mitigate moisture re-adsorption within the system. The resultant vapour was condensed, when possible, in two condensers installed in a row.

An integrated servomotor from Teknic, Inc. was used to rotate the screw at variable speeds with a maximum torque of 13 N-m. Multiple sets of cold flow experiments with wet train tissue, as the most similar material to the waste feedstock, were conducted to identify the approximate achievable residence times. Figure 4-2 showcases the effects of screw speed on material conveyance with the respective standard deviation for each RPM to assimilate the overall contribution of the waste and dryer physical characteristics on solid's conveyance.

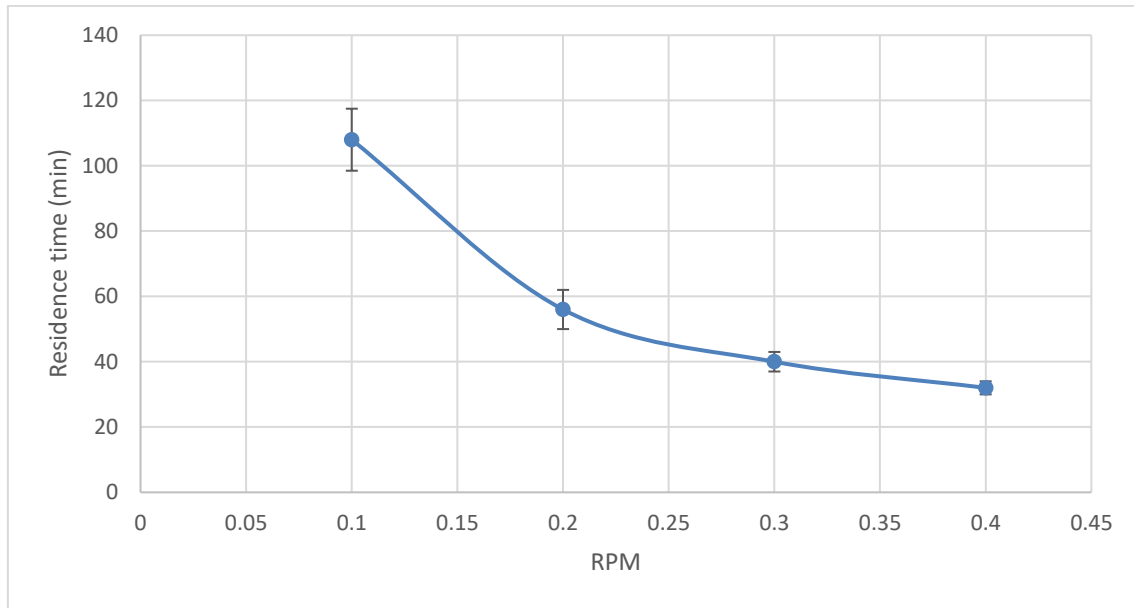


Figure 4-2 Residence time estimation

A hopper and collection chamber were installed on the inlet and outlet of the dryer to mimic the final integrated system and facilitate the testing phase. The hopper had a slider on top, which was shut when the feedstock was poured into the unit to reduce air ingress and mitigate the risk of biological hazards. Lastly, the unit was fully covered with 25mm ceramic fibre blanket to limit the heat dissipation and a convenient temperature control with PID devices.

4.2.2 Initial setup and commissioning

The overall design, setup, testing and optimisation were conducted under the Cranfield University ethics scheme, CURES/9346/2019 and CURES/7933/2019. Four K-type thermocouples were installed along the length of the dryer to understand the temperature profile within the reaction area in the order of channel 1 – 4 from the inlet towards the outlet. A single heating tape of 1.5 kW/h was wrapped around the unit primarily, operated by a PID device connected to a solid-state relay and a separate thermocouple (CTC) positioned in different sections of the unit in initial tests, depicted in Figure 4-3.

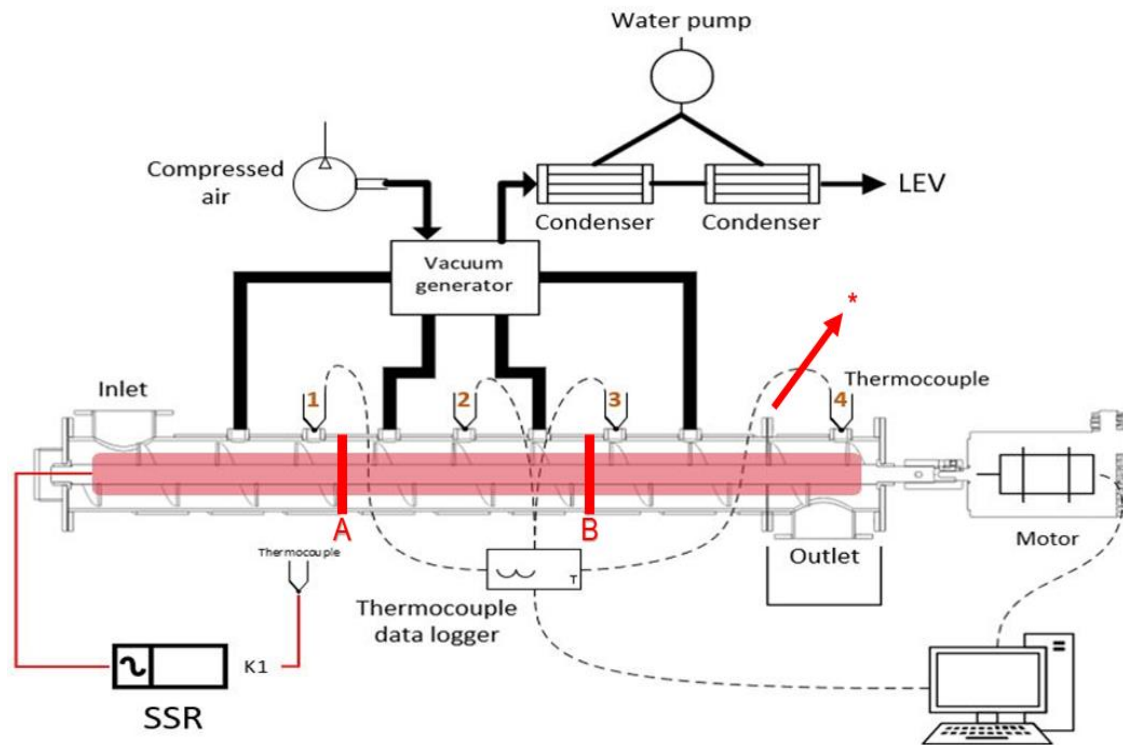


Figure 4-3 Initial dryer configuration (A, B: CTC positioning)

4 extraction pipes (stainless steel) were installed on the dryer which were connected to the vacuum generator to facilitate the vapour removal from the dryer, increasing the drying efficiency by mitigation of the chance of water re-adsorption by the solid matter.

4.2.3 Preliminary experiments

Through the primary set of tests, 200g of waste material were fed into the dryer at different temperatures and screw speeds.

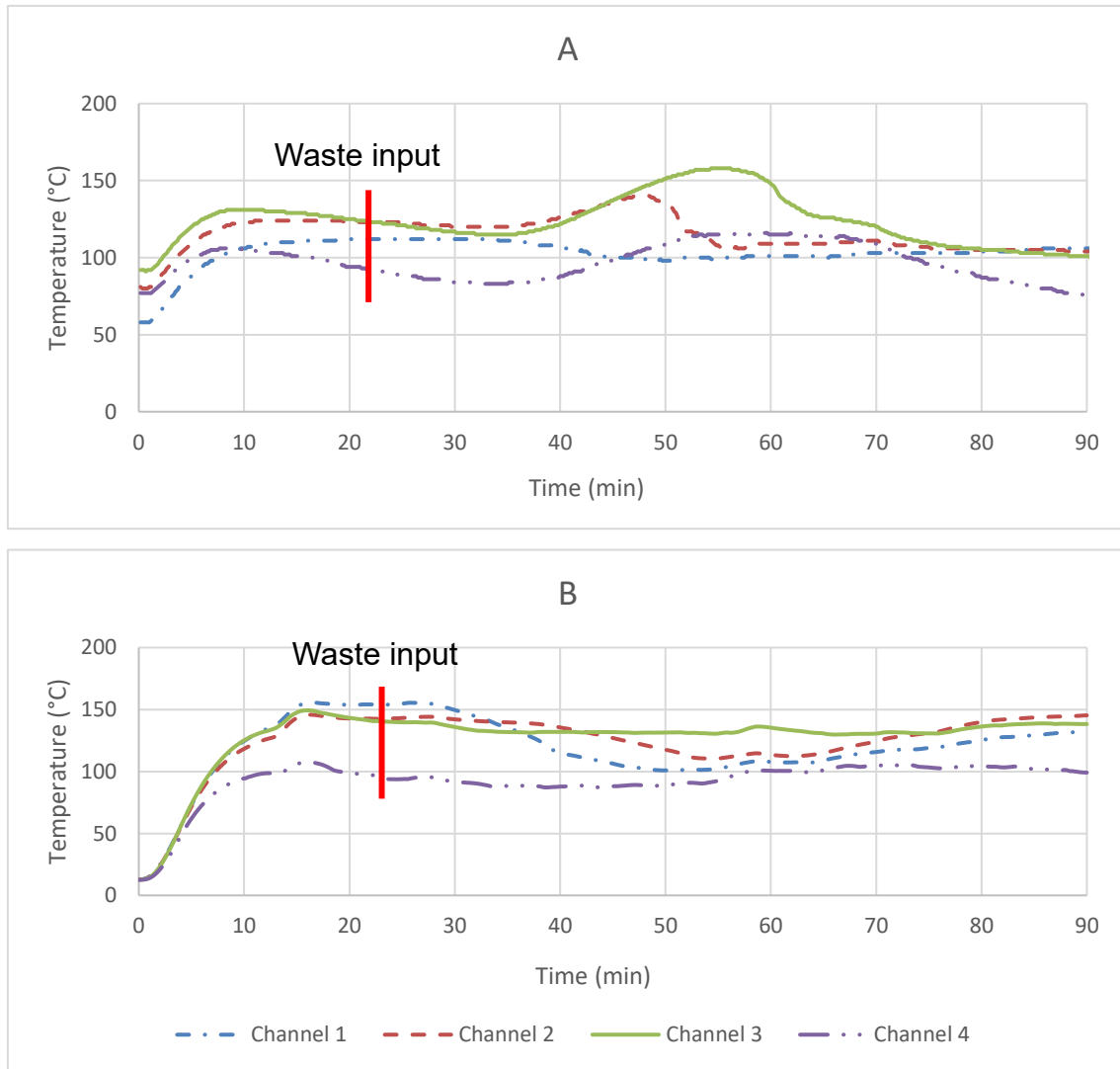


Figure 4-4 Unstable temperature profile within dryer: A) CTC positioned close to channel 1, B) CTC positioned close to channel 3

The temperature ramp up was not similar between different zones while, channel 4 always stayed lesser than others, since the heating tape was not covering the shell properly close to the outlet due to manufacturing, “*” in Figure 4-3. In addition, the number of turns around the shell for the heating tape led to a higher temperature ramp up in the respective zone. Illustrated in Figure 4-3, two spots were selected for the positioning of the CTC namely A and B on the surface of the shell. In the first case where the CTC is close to channel 1, through movement of the waste in the unit and adsorption of heat, upon reaching to the CTC zone, the heater is triggered and the temperature in further channels continue raising,

showcased in Figure 4-4, 'A'. Channel 1 stays almost constant at this point and when the waste passes the CTC zone, it is exposed to very high temperatures in further channels.

Meanwhile, in the case 'B' where the CTC is close to channel 3, the waste moving throughout the tube, adsorbs the heat and leads to temperature reduction in the first 2 channels while it has not reached the CTC zone. This configuration of heating assembly is not desirable since the product was either not dried, or it was partly burnt upon contact with the very hot surface of the unit when exiting the dryer. The fluctuation of temperature profile intensified when the CTC was replaced with one of the channels as temperature reduction took place intensively in the reaction area. In this application, the frequency of the feed entering the unit is unknown which could result in further fluctuations in the profile.

Overall, the temperature profile in such a design should be controlled using multiple heaters covering the unit to refine the effects of waste movement within the unit. Furthermore, utilising shorter heaters with lesser width can ensure a uniform heat transfer through the shell.

4.2.4 Final configuration and analysis

Concluding the alternative heating assembly, 3 heating tapes each 940 watt/h, were wrapped around the unit. The configuration of the piping on top of the dryer was alternated to enable the installation of thermocouples in the centre of each heated zone. Depicted in Figure 4-5, thermocouples and the respective heaters were connected to separate PID controllers. The extraction pipes were connected to a main pipe attached to a condenser for vapour condensation while the vacuum generator was installed on the outlet of the condensation flask. The overall configuration of the system for testing and the refined temperature profile are provided in Figure 4-5. Controlling the temperature with PIDs, a maximum hysteresis of 12 ± 3 °C was observed at various testing temperatures.

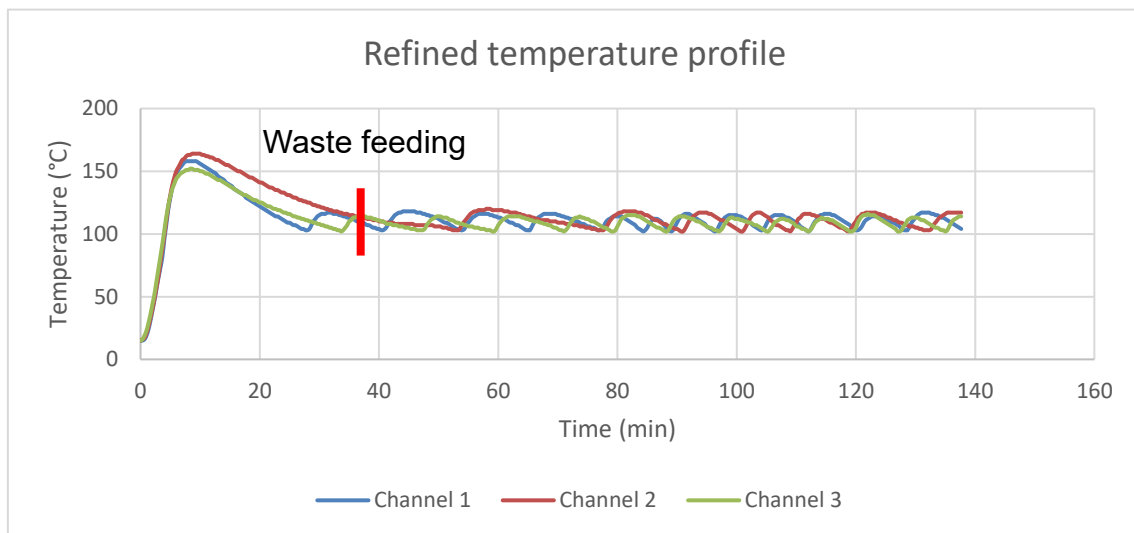
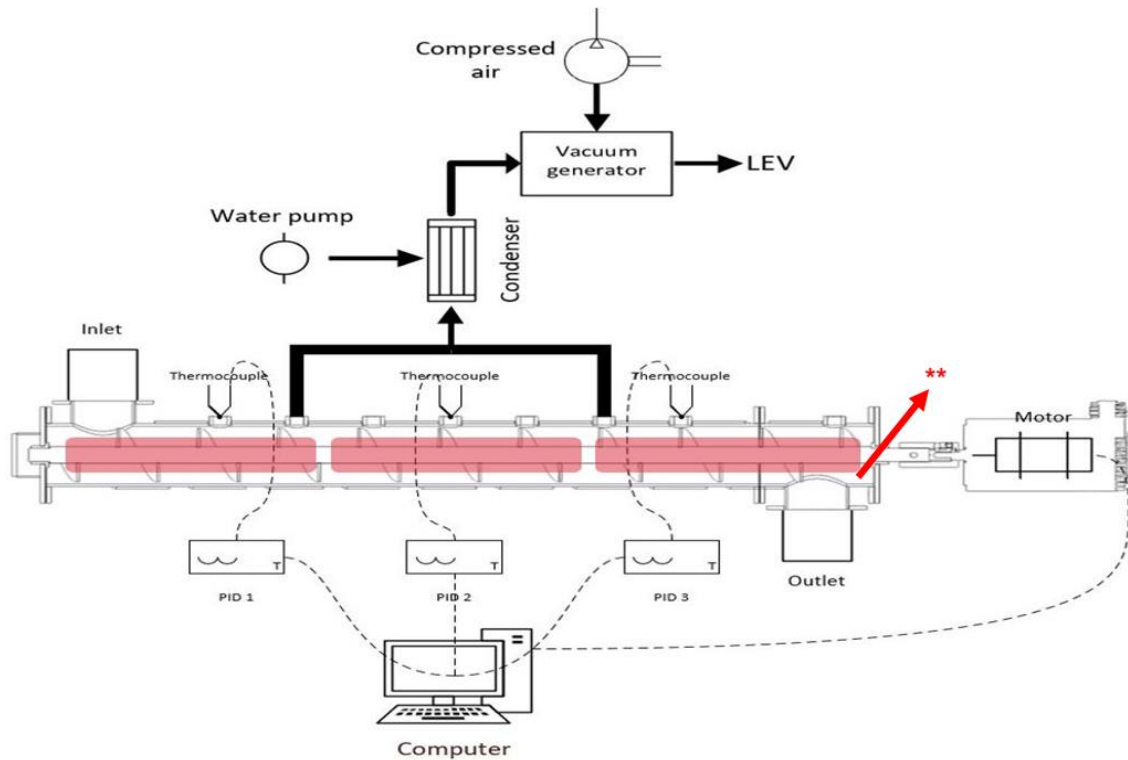


Figure 4-5 Final configuration of dryer for testing

The process parameters studied in this research included the high heating temperature (HHT), screw speed (RPM) and feedstock volume (FFR). In each step of the experiments the effects of process parameters on the drying efficiency were evaluated, analysing the moisture content of the partially dried products using the method outlined in BS EN ISO 18134-2. The tests were performed in

batches to resemble a toilet flush. Following this, the reduction in moisture was calculated based on the equation below [156]:

$$\text{Reduction in moisture (\%)} = \frac{\text{Initial} - \text{Final (moisture wt. \%)}}{\text{Initial (moisture wt. \%)}} * 100 \quad (4-1)$$

In addition, the carbon content in the solid products were determined through elemental analysis to highlight the carbon emission for drying temperature tests (HHT). Lastly, the vapour products from HHT experiments were analysed with an ion-chromatographer, Dionex ICS -1600 and ICS-900 with Dionex-IonPac CS12 250*4mm column for the content of anions and a cation (Ammonium) respectively, to understand the inorganic contribution from the dryer within the overall ClearTrack system. Prior to each experiment, the condensation tower was thoroughly rinsed with plenty of acetone and distilled water to ensure no cross-contamination.

Thermal drying has been commonly used for volume reduction and sanitation of biosolids generated from wastewater treatment plants [157]. In addition, nutrients in sludge are a prospect for the production of high value fertilizers [158]. However, through thermal drying the soluble nutrients enter the condensate affecting their fertilization value [157]. In this application, it was aimed to preserve the nutrients and other inorganics within the system and prevent them from entering the pyrolysis unit and consequently the products prior to disposal.

4.3 Results and Discussion

The intensive weight loss of the waste sample due to the breakage in organic bonds occur at a temperature ranging from 250 to 450°C while staying negligible below 200°C [159]. Using the results from earlier TGA experiments on faecal sludge samples and their chemical characteristics, 3 temperatures of 105°C, 125°C and 150°C were selected for the testing of the dryer to ensure negligible emissions from the unit.

Table 4-3 Process conditions during 3 test phases

Test Phase	Temperature (°C)	Screw Speed (RPM)	Feed input (g)
HHT	105, 125, 150	0.2	100, 160
RT	150	0.1, 0.15, 0.2, 0.25, 0.3	100
FFR	150	0.2	100, 250, 400

For the commissioning of the newly built dryer, tests for high heating temperature (HHT), residence times (RT) and feedstock flow rate (FFR) were conducted in order under some of the conditions explained in Table 4-3. Products from two repetitions of each test were analysed twice for their moisture content and their average was accounted. Following the interpretation of the results, desirable process parameter from each stage were used for the further steps in testing.

4.3.1 Drying efficiency

Choice of 0.2 RPM for the HHT tests was based on the outcomes from initial cold-flow tests to enable a minimum of 45-minute residence time for the fluidised sludge within the dryer. Depicted in Figure 4-6, duplicate analysis of each test confirmed that the extent of evaporated moisture content increased with the higher temperatures up to 42%, calculated by equation (4-1), for 100g as the minimum feed volume entering the unit per toilet flush.

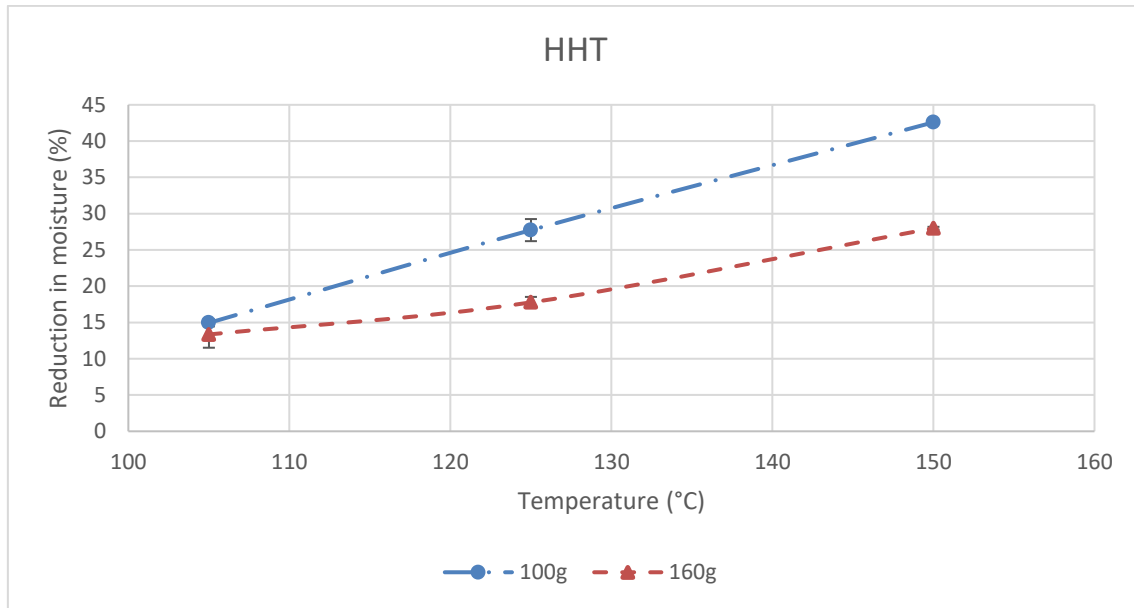


Figure 4-6 Effects of HHT on drying efficiency

Drying rate increased with higher temperatures as high as 150°C similar to other studies [146]. In the case of 160g (average volume/defecation), the rate of drying stayed negligible between 100-125°C while elevated as the temperature was increased from 125 to 150°C. In a study on the drying of sewage sludge, the drying rate was improved from 0.51% to 0.76% per minute with the temperature changing from 100°C to 150°C while the residence time also played an important role in the drying rate [160].

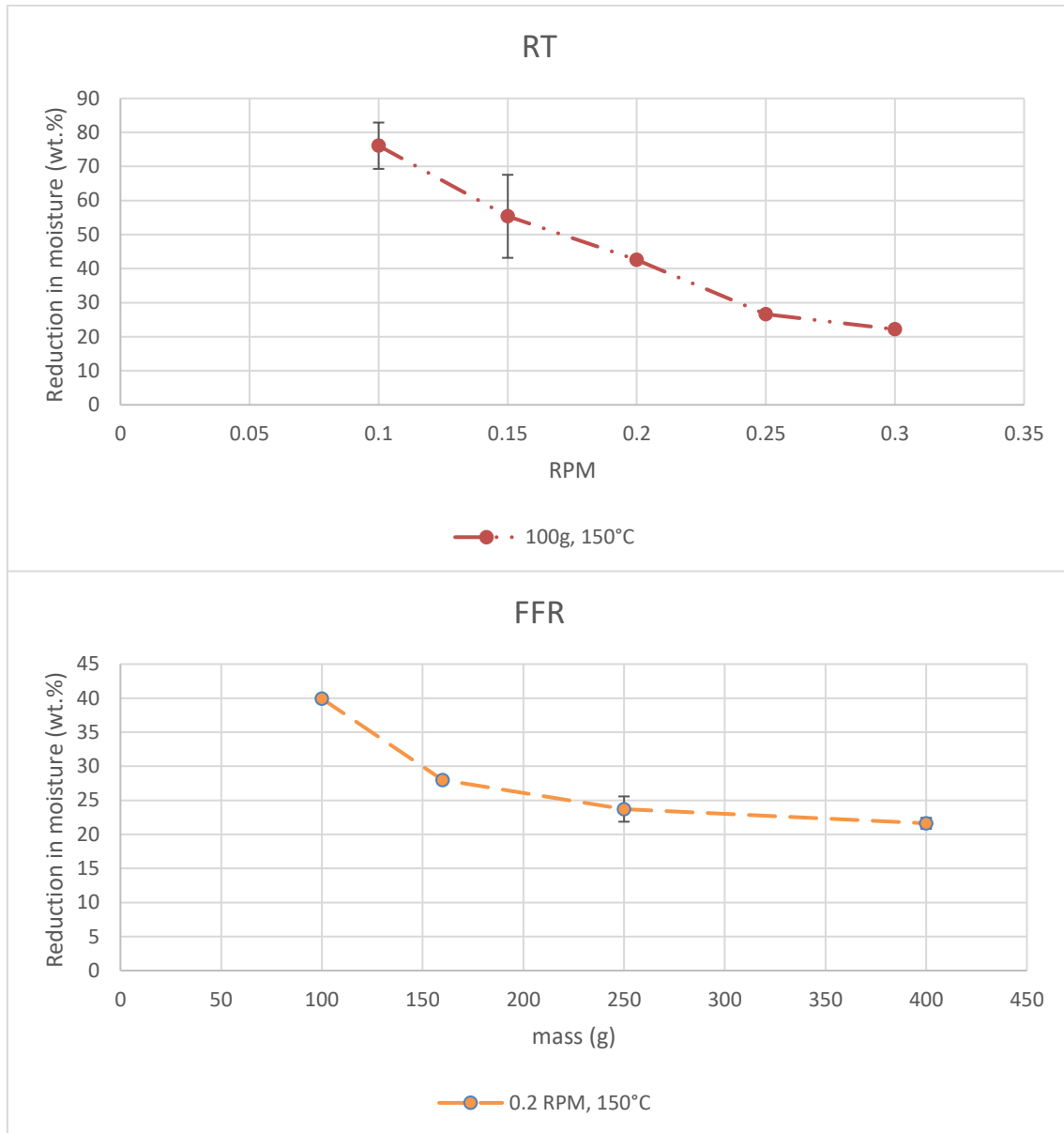


Figure 4-7 Effects of RT and FFR on drying efficiency

Taking advantage from the interpretation of the results during HHT tests, 150°C was selected as the optimum temperature to yield the highest drying efficiency for any mass/volume of feed entering the dryer. Assessment on the effects of prolonged residence time in duplicate tests with the sludge collected from different trains showed an achievable evaporation rate as high as 82% at a screw speed of 0.1 RPM, depicted in Figure 4-7. However, notable inconsistencies in the product's moisture content were observed through drying with screw speeds

lesser than 0.2 RPM. This was potentially due to a non-uniform agitation and fluidisation of sludge within the unit. Through these tests, the products exiting the unit had a large granular shape implying the conveyance of large volume of input feed in between a single pitch of the screw which limited the moisture diffusivity and depleted heat transfer through particles, depicted in Figure 4-8. Reported by Grüter et al. (1990), sludge undergo various physical consistencies through drying, free-flowing pulps to pasty (sticky zone) and granular shape in order [161]. Zhu et al. (2012), studied the drying efficiency of sewage sludge within an electro-thermostatic blast oven in different shapes (cylindrical, spherical and cake) and concluded the direct relation between the specific surface area of sludge with reduction in moisture [159]. Authors concluded that the higher specific surface area in the case of cake sludge enabled higher drying efficiency due to the removal of moisture from inside the sludge samples.

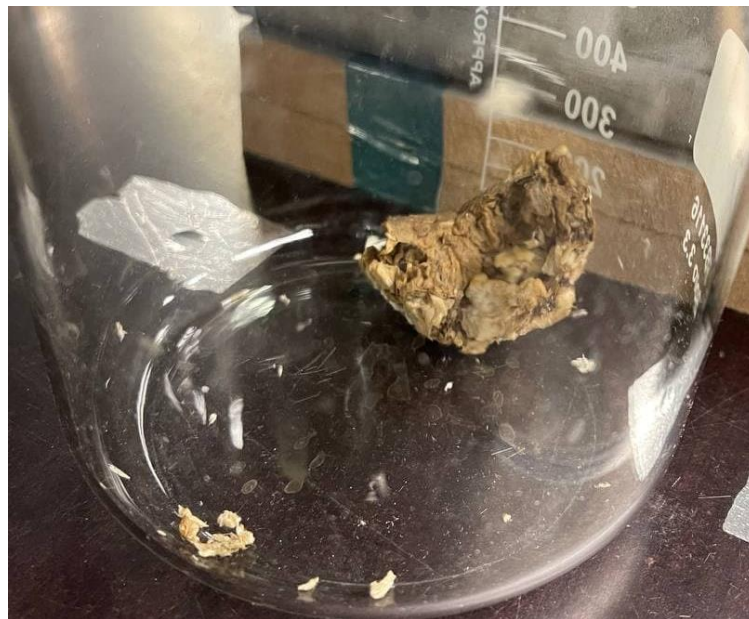


Figure 4-8 Large granules formed at screw speeds lower than 0.2 RPM

Another potential reason was the difficulty with effective emptying of sludge through the outlet. Depicted in Figure 4-5, the zone marked with ‘***’ shows a gap between the outlet and the bearing where the sludge stuck to the screw flights or the large granules which exceeded the outlet in diameter accumulated and resided in the dryer for a longer period. Unfortunately, research in the application

of screw conveyors for drying of sludge materials are scarce with this application remaining unexplored to the best of our knowledge.

Selecting 0.2 RPM as the suitable screw speed for processing with such dryer, assessment on the impacts FFR on drying efficiency showed almost 20% lesser reduction in moisture content as the feed input was increased from 100 – 450g. In addition, it proved the high sensitivity of the dryer in moisture reduction when the mass of input varied between 100 – 200g which stayed negligible ($\pm 4\%$) from 200 and after up to 400g. Increasing the mass to 250g and further resulted in similar moisture content discrepancies observed with slow screw speeds in two different trials while the exiting granules were in large lumpy shapes. Research on the drying of sludge has already proven the prolonged required drying time at a constant temperature once the mass of input increases [143]. Guo et al. (2021) studied the microwave drying behaviour of sewage sludge in a pilot-scale system running in batch mode which confirmed 126% increase in drying time as the mass was changed from 500 to 1500g [160]. Authors reported an enhanced moisture diffusivity when the thickness of sludge was lesser while maximum drying rate was observed with a 500g FFR and observed partial overlaps in the case of 1250 and 1500g.

4.3.2 Elemental carbon reduction during drying of sludge

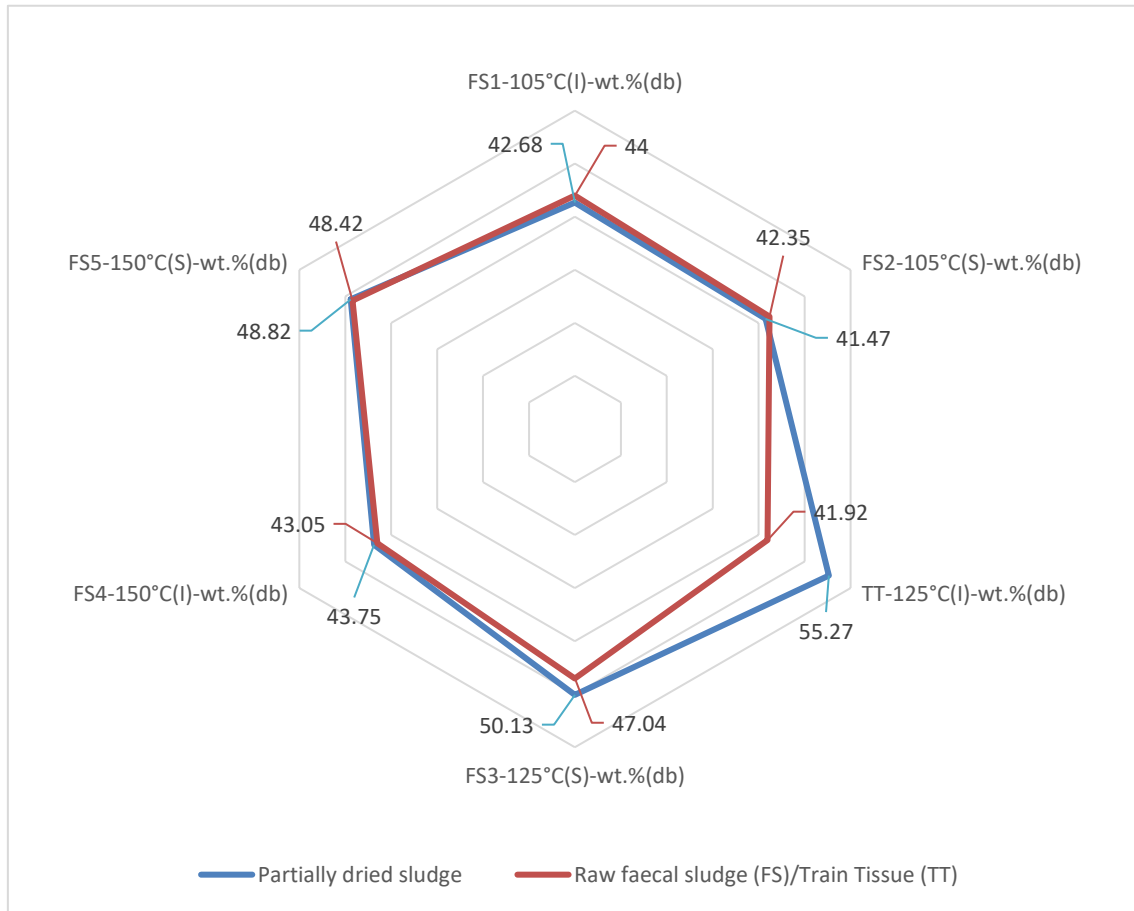


Figure 4-9 Difference of elemental carbon content between partially dried and raw faecal sludge in HHT tests⁴

To understand the magnitude of elemental carbon emission through drying at different temperatures, the carbon content of the internal (I) and surface (S) part of the partially dried granules from duplicate tests at different temperatures were analysed with elemental analyser from ELEMENTAR (vario EL). The radar graph in Figure 4-9 showcases the carbon content in dried samples against that of raw sewage sludge or tissue paper (used on trains). Results are evident that the developed single screw dryer is able to ensure the removal of moisture content

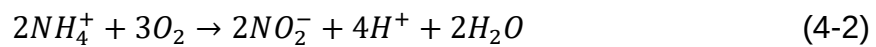
⁴ Explanation of data points; FSx or TT{raw faecal sludge or raw Train Tissue analysed for elemental carbon}-Drying temperature of the dried granules (analysis on the Internal (I) or Surface part (S))-wt.% of carbon reported on Dry Basis (db)

from various waste streams at temperatures up to 150°C with negligible volatile emission.

Findings from a study by Getahun et al. (2020) confirms the negligible rate of volatile compounds extracted from multiple types of faecal sludge samples up to 150°C while almost 30% reduction in calorific value was observed when the drying temperature was increased to 200°C [146]. In another study on the drying of sewage sludge using thermal gravimetric analyser, Qian et al. (2011) faced an excessive reduction in weight once the temperature reached 250°C, more than the weight of sample's moisture content determined using common proximate analysis methods [145].

4.3.3 Inorganic evolution

Typically, urine and faeces contribute 75% and 20% to the nitrogen content in wastewater respectively, in various formats such as water-soluble Nitrate, Nitrite, Ammonium and Ammonia as well organic N [163] [8]. Most of the soluble nitrogen are commonly removed from sludge through the dewatering stage leaving a low fraction of N for the condensate, a product of thermal drying which is associated with organic nitrogen depending on the unit's operating condition [164]. The dominant forms of nitrogen in wastewater are ammonium, ammonia and nitrate/nitrite products of ammonification and nitrification respectively while the nitrite remains as an intermediate product of nitrification during which ammonium converts to nitrate [165] [163], following the equations (4-2) and (4-3):



Effects of temperature on the flushing of nutrients in the liquor phase were assessed and the results of anion fluxes in the condensate for two rounds of HHT test and a single RT, as the core process conditions, are illustrated in Figure 4-10.

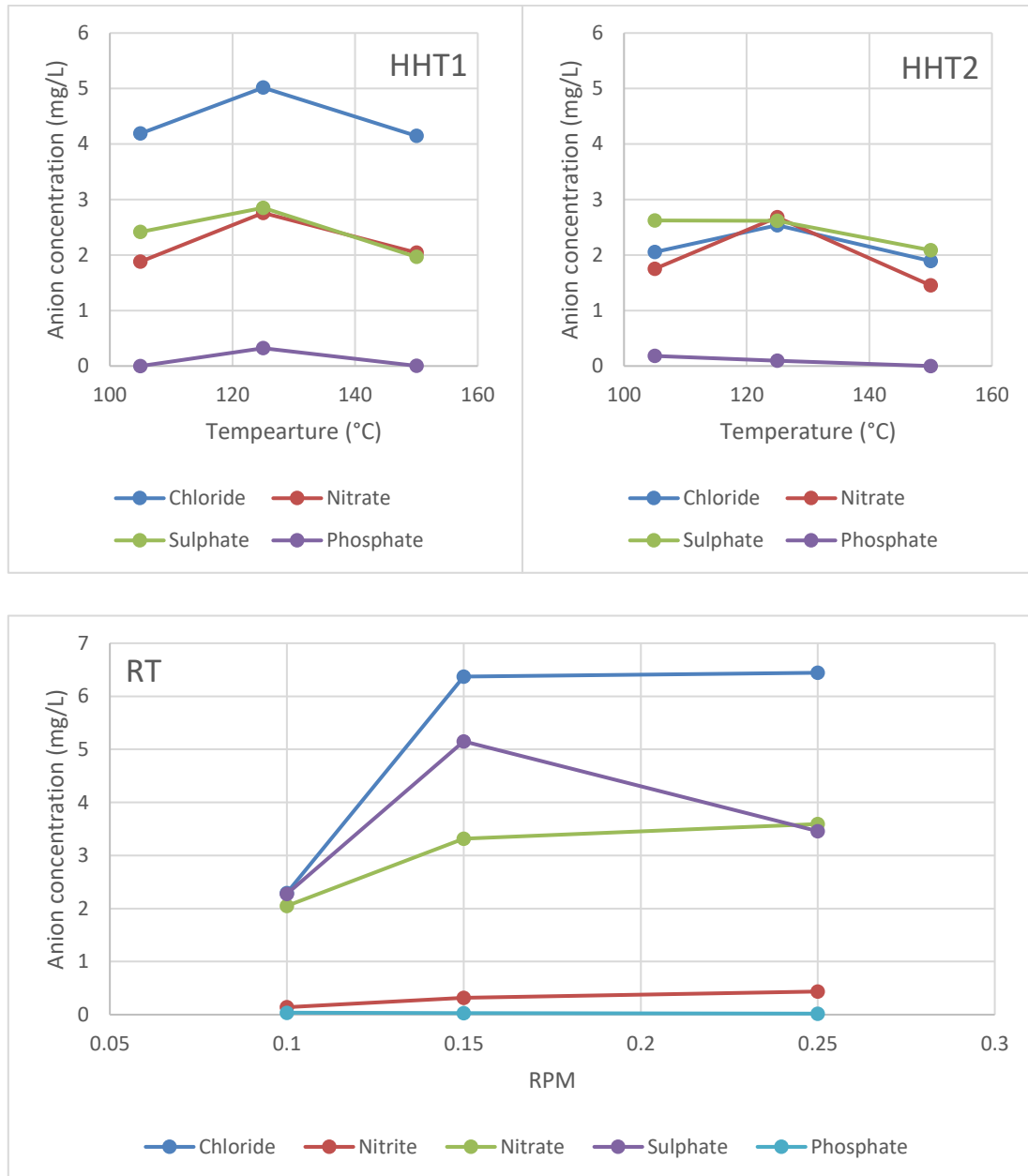


Figure 4-10 Anion concentrations in condensate

Since the dryer is developed as a part of a wastewater treatment system, the content of inorganics extracted with vapour from drying process are significantly important for the planning of water purification system. This could help the selection of suitable methods for the removal of various inorganics and upgrading of the water to flush standards. The obtained data highlight the notable effects of sludge properties on the flux of nutrients in the condensate while the nitrite

concentration was negligible in most of the tests and is not provided in the graphs for HHT tests. Various ranges for the content of nitrogen and phosphorus in faecal sludge and domestic wastewater are provided by Strande et al. [8]. An observation was the accelerated flush of nutrients as a results of temperature escalation with a peak around $125^{\circ}\text{C} \pm 8$. There was 8°C fluctuation in the temperature was due to the hysteresis in heat profile generated by PID controllers. Research on the faecal-/sludge drying and thermal treatment is very scarce, and this study is considered as one of the very first researches exploring the impacts of drying on such faecal sludge extensively. Furthermore, reduction in residence time at 150°C showed an unimportant rise in the content of nitrate and nitrite which are potentially ascribed to nitrification of abundant ammonium through microbial conversion, Figure 4-10. Meanwhile, the sulphate and chloride⁵ did not indicate a reasonable pattern highlighting the importance of the chemical properties of the raw sludge.

Unfortunately, cation analysis on the condensates were delayed due to supply chain issues of regenerants for the Ion chromatographer during COVID and the liquors from dryer were disposed. This was to reduce the effects of microbial conversion of nitrogen compounds which were stored in fridge for a long time. Additionally, collection of faecal sludge from train depots was restricted and sludge volumes did not allow complete sets of tests. Hence, only two further HHT and RT tests at 105°C , 150°C and 0.1 - 0.3 RPM were conducted again, and the condensates were analysed for their ammonium content to understand their evolution. The alteration of temperature at a constant screw speed of 0.2 RPM almost doubled the content of ammonium in the condensate from 596 to 1145 mg/L implying the most abundant N-compound in the faecal sludge. Meanwhile, lower residence time at 0.3RPM shifted the ammonium from 1127 to 790 mg/L. The increase in the content of NH_4^+ is strongly due to volatilization of NH_3 which

⁵ Results of chloride include some discrepancy as the chromatograms included a broad peak interfering with chloride indicating acetic and propionic acid. (Emissions were a result of tests and mostly due to excessive temperatures during ramp up phase by PID controllers emitting carbon from the fouling sludge, 200°C in the case of 150°C tests.)

is accelerated at higher temperatures of 190°C in other studies indicated by PH measurement, a consequence of shift in NH_3 and NH_4^+ equilibrium [157].

Sun et al. [166] studied the effects of hydrothermal process on the nutrient release of sewage sludge between temperatures of 180 – 240°C and stated a significant (40-70%) solubilization of nitrogen into the condensate. However, at temperatures below 200°C, temperature played an insignificant role in contrast to residence time. Authors reported the hydrolysis of N-compounds to amino acids, organic-N and ammonium up to 160°C which is followed by deamination and hydrolysis of amino acids to ammonia at temperatures higher than 180°C. In addition, prolonging the residence time up to 60 min at 180°C resulted in major change of NH_4^+ , whereas another 30 min extension obtained 8% rise in the content of ammonium. Presence of carbon compounds in ion chromatograms suggest the necessity of the determination of ammonia to shed light on the whole N-compound evolution. Reported in literature [157], following the degradation of carbonates, H^+ consumption was observed to yield higher NH_3 at escalating temperatures of 190°C to 250°C.

Depicted in Figure 4-10, phosphorus content stayed very low as it has an affinity for the solid phases [167]. Lemming et al. (2017) observed the negligible effect of drying at 70°C on the water extractable phosphorus from various sludge samples which increased to almost 5% at higher temperatures with an exception at 190°C [157]. In addition, only 10 – 15 % of P was extracted from sewage sludge processed at 180 – 240 °C during 90 minutes of residence time. During FFR tests, the vacuum system extracted particles of sludge due to high masses of sludge which blocked the vapour exit ports. Hence, the results were not taken into account.

4.4 Conclusion

An innovative screw drying system for volume reduction and inorganic removal from faecal sludge generated in on-board train toilets was developed and commissioned considering the technical criteria and constraints. A program of analysis was carried out to identify the impacts of various process parameters on

drying efficiency as well inorganic extraction from faecal sludge. Assessment on drying temperature revealed an optimum heating of 150°C ensuring negligible carbon emission from the unit. Mechanical fluidisation of sludge, as the key parameter in screw conveyor systems was evaluated suggesting approximately one hour of residence time for consistent moisture removal in batch operating mode. However, flowrates and feedstock chemical properties were found to perform a crucial role, impacting the robust operation and persistent efficiency of the unit. Further exploration of screw shapes and sizes are needed to eliminate the sensitivity of drying efficiency to low volume feed inputs. The manufactured dryer was unable to effectively reduce moisture content of sludge once the feed flow rate exceeded 250g. Hence, authors claim an enhanced performance upon utilisation of twin augers to boost the heat transfer through better fluidisation.

The dominant form of nitrogen in the faecal sludge was ammonium with a higher sensitivity to the operating temperature in comparison to a prolonged residence time. For future studies, determination of total nitrogen content including ammonia in both gaseous and liquor form for different wastes from CET are suggested to comprehensively characterise their impact on the whole wastewater treatment system.

Typically, carbon emission has stayed negligible through temperatures below 160°C, reviewed and showcased throughout this study. However, understanding the chemical oxygen demand of the condensate could further highlight precise carbon emissions from the dryer. This research remains limited in the optimisation program since other variable need to be investigated with the product yield and properties to deduce an optimal operating condition. A well-known technique for the optimisation of chemical reactors is the response surface method (RSM) [168]. Combination of this technique with central composite design explores the relations between process variables and system's response to enable the satisfaction of operating specifications while reducing the number of experiments [169].

Chapter Five

5 Design and Chemical Process Optimisation of a Twin Auger Pyrolysis Reactor

This Chapter outlines the design and setup of the novel pyrolysis reactor for commissioning. The effects of process parameters playing the key role in this application on the properties of pyrolytic products are identified through their complete chemical characterisation. Design implications and contributions to knowledge on the pyrolysis conversion of such solid wastes are comprehensively covered.

Abstract

For the first time, an innovative twin auger pyrolysis reactor for the intermediate conversion of wet sanitary faecal sludge generated on trains (mobile applications) is designed and successfully commissioned. The effects of operating temperature, feedstock feeding rates and moisture content and their interaction on the distribution and properties of product biofuels with the use of no carrier gas assessed. Approximate yields of 50%, 40% and 10% were observed for the biooil, syngas and biochar respectively at 500°C. Meanwhile the highest calorific value (HHV) of the syngas remained close 10 MJ/kg. Acidic compounds (10% RPA) and nitrogen-containing hydrocarbons (18% RPA) substituted the abundant species in biooil fraction at 500°C with the lowest feeding rates of feedstock. Biochar calorific value presented the high fixed carbon (58%) and ash content (37%) with the higher temperatures for the minimum and maximum flowrates of feedstock. Interestingly, the retention of inorganics within the structure of char are observed. Effects of reactor design and configuration on the pyrolytic products are discussed accordingly and further implications are provided. Overall,

extensive further research for the end-use of pyrolytic products and the investigation of emissions, upon energy recovery or land-application of by-products, are suggested.

5.1 Introduction

In this study, the development and commissioning of a pyrolysis reactor is outlined and the thermochemical conversion of faecal sludge is assessed to shed light on the overall performance such system. Implementation of thermal treatment technologies for the decentralised sanitation of human wastes has been recently identified as a cornerstone for proper faecal sludge (FS) management [6]. Researchers have extensively investigated the applicability of combustion and gasification processes to provide rapid, energy-efficient and environmentally friendly solution to the improper disposal of this hazardous waste [107] [109]. However, major challenges for the automation and optimisation of these processes due to high heat fluxes and the fuels physiochemical characteristics within the reactor were observed [6] [108]. Meanwhile, the application of small-scale pyrolysis for sanitation of FS is barely explored with a few ones investigating the principles in lab scale [170] [130]. These technologies are commonly known to be suitable for low-income countries or situations where sewage infrastructure is inaccessible or difficult to be accessed. In 2019, GBR-Rail Ltd. in collaboration with Cranfield University kicked off the ClearTrack project to develop an on-site wastewater treatment system for trains. The generated faecal sludge in on-board train toilets have been conventionally stored in a controlled emission tank (CET) for further emptying in depots using extraction pumps [3] [4]. The proposed system is comprised of an effluent purification and recovery loop as well as an innovative thermal treatment system for the primary and final stabilisation of highly wet hazardous faecal sludge. This work follows the findings from our previous study [6], on the selection of pyrolysis as the suitable technology for these applications and further evaluates the performance of a novel pyrolysis system designed and commissioned with the associated technical and operational constraints.

Pyrolysis is the thermal degradation of the organic matter taking place in a non-reactive atmosphere at temperature ranging from 300 to 700 °C depending on the type of biomass and process conditions [171]. Through the pyrolysis stage of a fuel, various fractions such as non-condensable (syngas), condensable (bio-oil) and a solid fuel (bio/char) are formed [172]. The composition and yield of the products are heavily dependent on the process conditions whilst very high heat fluxes (~600 °C) and short solid residence times (fast pyrolysis) favour the production of liquid bio-oil products. Moreover, lower heating temperatures and longer residence times (slow pyrolysis) contributes to the production of solid char [173].

However, the main application of this process in commercial scale is known to be the maximization of the liquid yield [139]. In addition to high heating temperature, heating rate and residence times, the pyrolysis efficiency and product specifications is affected by the raw fuel characteristics such as moisture content and particle size [6]. Hence, various stages of pre-treatment might be implemented to further reduce the size and moisture content (<10% wt.) of the waste [139].

Conventionally, different reactor designs and process principles are used for the pyrolysis of various types of biomass and waste materials such as Rotary kilns, rotating cone and ablative processes to facilitate the application constraints and render a desired product for energy applications [173]. High heat and mass transfers are achievable from reactors such as bubbling and circulating fluidised beds (BFB and CFB respectively) associated with high levels of operational complexity whilst requiring large quantities of carrier gas. More information on the existing pyrolysis technologies and reactor designs can be found elsewhere [174]. In addition to the aforementioned reactor designs, auger reactors are considered to provide a high technology strength and market attractiveness [175]. This technology provides mechanical fluidisation of the waste through the length of the reactor in the presence of heat carrier materials (i.e. hot sand) for mainly fast pyrolysis such as the twin auger reactor designed in the IOWA state university [176] or convective heating of the tube for slow and intermediate

modes of pyrolysis [177]. Utilisation of auger reactors have been extensively researched for various types of biomass and waste solid materials [173] [171] [178]. Morgano et al. (2015) carried out the pyrolysis of beech wood chips achieving 13.2 wt.% bio-oil at 450 °C and observed a reduction of 13 wt.% in the yield of char through temperature change from 350 °C to 500 °C [179]. Yu et al. (2016), Observed a declination in the yield of char through temperature escalation while the change in temperature from 350 °C to 600 °C contributed to the higher yield of gas by 13% and 11% for rice husk and corn stalk respectively [180]. Of the advantages of screw pyrolysis reactor are their suitability for mobile application with limited infrastructure and lower energy demand due to the smaller specific size of the reactor [171]. Furthermore, the design is capable of handling various raw material with variable particle sizes. Typically, the gas residence times are higher in augers in comparison to BFB and CFB which should be of no disadvantage when the goal is a higher yield of non-condensable fraction [180]. In addition, the prolonged gas residence times in auger reactors favour the production of more char at the expense of liquid oil which could be mitigated by introducing exit ports along the reactor if the condensable fraction is desired [181].

This work aims for the development and commissioning of a twin auger pyrolysis reactor for the stabilisation of human faecal sludge generated in on-board train toilets. Utilisation of twin screw pyrolysis reactors enable an enhanced mixing and dispersion of feedstock through intermeshing for an effective heat transfer through particles [173]. This configuration not only reduces the required power for auger rotation but also enables a more complete feedstock conversion. Additionally, these reactor configurations result in the cleaning of sticky materials plugging on the screw flights which potentially form in the case of single screw reactors [182].

5.2 Methods

5.2.1 Design and fast prototyping

Testing and optimisation of the unit was carried out under the Cranfield University ethics scheme, CURES/9346/2019 and CURES/7933/2019. A schematic of the ClearTrack system is provided in Figure 5-1, through which the wastewater undergoes a dewatering stage where the faecal sludge from each toilet flush is separated from the effluent and fed into a drying unit. Following this, the feedstock is partially dried, and the nutrient-rich condensate generated through evaporation of moisture is directed towards the effluent treatment system. The dried faecal matter throughout one day of train operation (the operational timeframe is heavily dependent on the type of train, their journey and the number of stops until destination) is accumulated in a storage chamber which feeds the partially dried FS into the pyrolysis reactor via mechanical means. The rationale behind the implementation of the chamber is the low and alternative flow rate of solids at each toilet flush which forced the batch processing of the waste while reducing the energy consumption in comparison to constant operation of the reactor. Finally, upon applying thermal loads, FS undergoes pyrolysis degradation with an aim to maximise the reduction of char, the essential rule for hazardous waste treatment [6], and boost the production of syngas with the highest yield and calorific value. Production of high-quality syngas enables the chance of convenient energy recovery through combustion and limitation on energy consumption of this system via recycling of the heat which are suggested for future studies.

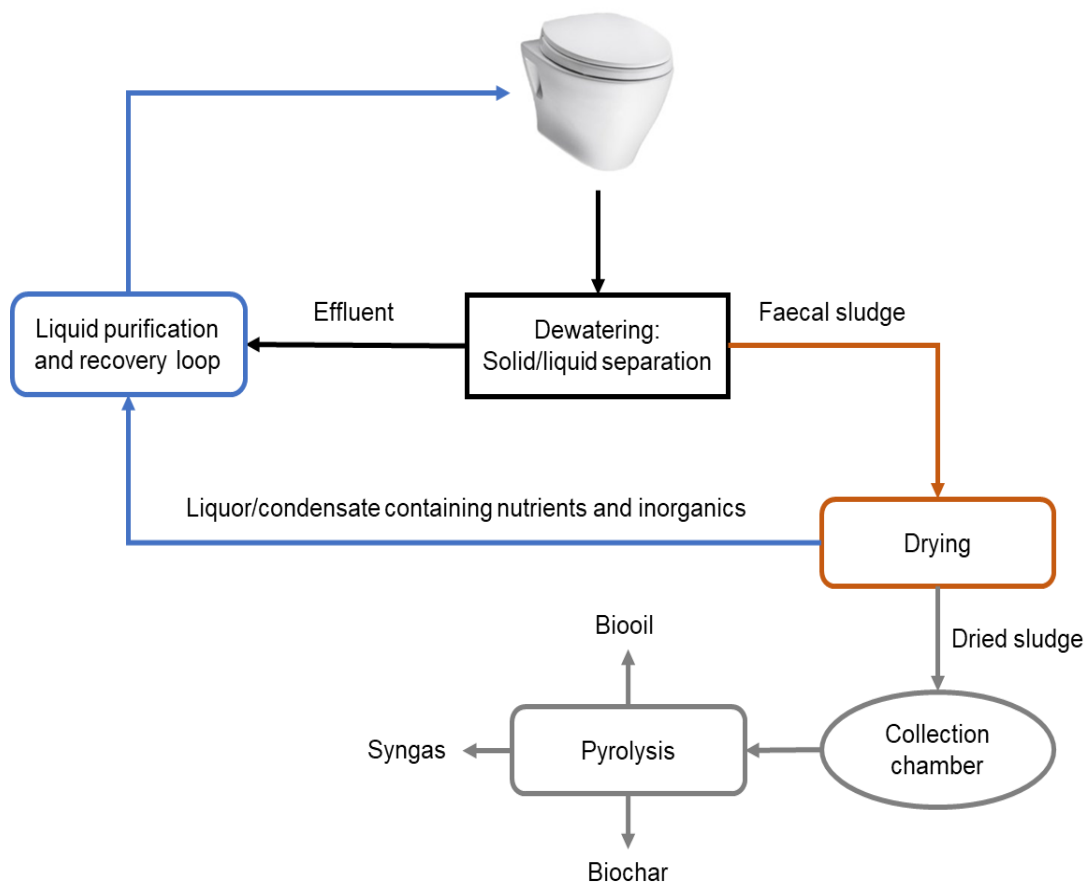


Figure 5-1 ClearTrack's solid waste stabilisation system schematic

In order to obtain an insight on the possible waste stream flow rates generated in on-board train toilets, literature data on the performance specification of a next generation closed loop sanitation systems for rolling stock were referred to [3] [4]. Described in Table 5-1, the reported values of the median daily adult human faeces generation rates vary ranging from 35g to 796g [148]. Hence, an assumption was made for the average value as 160g/cap/day for both adult men and women to pursue with the calculation of mass flow rates for the primary design of the prototype. In addition, an arbitrary amount of tissue (16g) per defecation was considered in the calculation. Finally, a safety factor of 2 was considered for all the parameters affecting the mass balance of faecal sludge in the system. It is notable that the assumption of safety factor for the number of defecations per day increases the total mass of faecal sludge entering the system. However, this is different to that of the mass of sludge per defecation that

affects the drying efficiency of the dryer unit. Multiplication of all the parameters by the safety factor leads to an overall total solid generation of ~11 kg/day. The described calculation method could potentially predict the worst-case scenario for the waste streams that enters the solid waste thermal treatment system in one day of the train's operation for long journey trains. The obtained figure represents a maximum value for the total mass flow of faecal sludge on the toilets of any trains. This number is predicted to be more practical for trains with longer journeys and lower number of stops. However, Lower feedstock flowrates will be tested for in this study to understand the system's behaviour.

The fast-prototyping process of the pyrolysis reactor was primarily based on the fundamental mass transfer in screw reactors, followed by the thermodynamic calculations to predict the fuel and product residence times for the pyrolysis reactor. Literature on the design and fabrication of screw conveyors for thermal processing were referred to [176] [183]. Details of the calculations are described below and provided in Appendix D.

Table 5-1 Calculation of the average faecal sludge mass flow rate on a daily basis for every train toilet

Ref.	Literature	Assumption	Safety factor (*2)
[3]	200L CET fills up with 167 toilet visits out of which 21 visits are for defecation.	16 visits for defecation were assumed	32 defecation/day
[4]	average of 125 toilet visits per day		
[149]	Median faecal wet mass 128 g/cap/day	Average weight/stool for both men and women were assumed as 160g.	Total solid weight of 352g/defecation
[184]	Wet wt.% 110-170 g/cap/day		
[150]	250 and 111.3 g/stool for men and women respectively		

Typically, the efficiency of the thermal drying process is reported between 20 to 70% [185] with the screw dryer being approximately 50% [183]. Hence, a diagram for the overall functions was generated to clarify the potential mass flow of the dry matter and moisture in each phase, Figure 5-2. The mass balance for the pyrolysis reactor upon conduction of heat to the sludge feedstock could be noted as:

$$\frac{dm}{dt} = \dot{M}_{FS} - \dot{M}_{GP} - \dot{M}_{CH} = 0 \quad (5-1)$$

Where $\dot{M}_{FS}$, $\dot{M}_{GP}$ and $\dot{M}_{CH}$ are the mass flow rates of the FS, gaseous products, and the solid char in kg/h respectively. This steady state analysis assumes all biochar exits within the length and the gaseous products include the condensable, non-condensable and aerosol fractions. The fast-prototyping process was continued by considering the pyrolysis reactor as a screw conveyor whilst various constraints due to the application was considered.

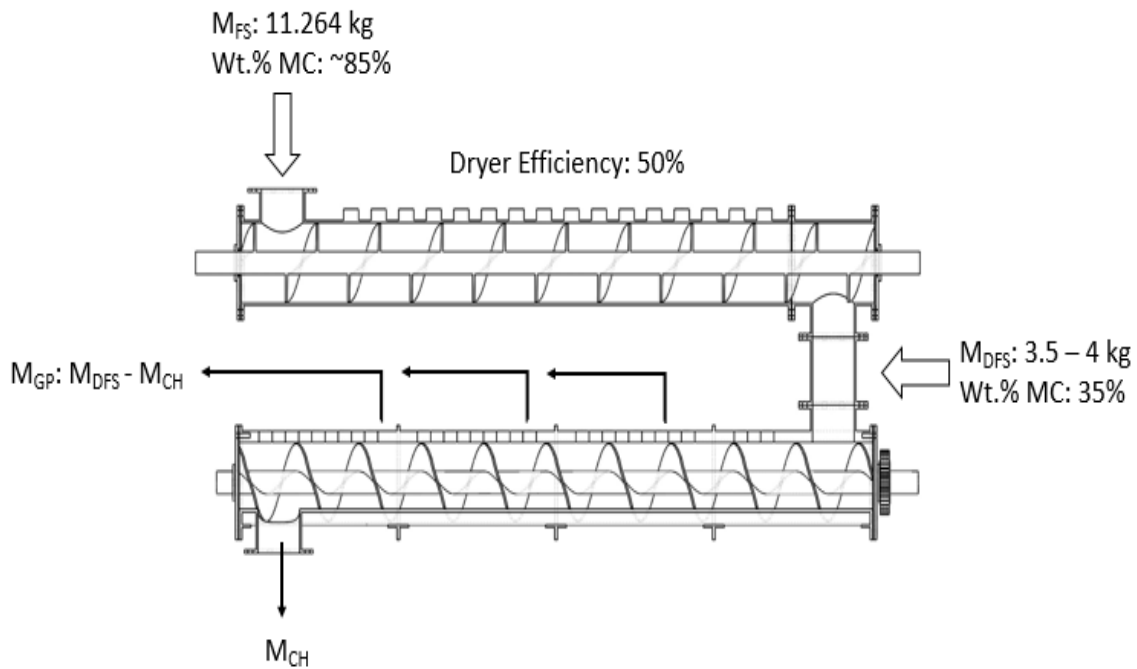


Figure 5-2 Mass flow schematic within ClearTrack system

Twin auger reactors are known best to mitigate the chance of clogging whilst improving the conversion efficiency of the biomass with their higher mixing rates [186]. In this design, the effective means of thermal load for heat supply were conductive and so the counter rotation (up-pumping) of the intermeshing twin augers were provisioned to maximise the heat transfer through particles upon contact with the whole heated circumference of the reactor. However, down pumping with counter rotation of screws is observed to better enhance the mixing behaviour of the materials inside the reactor and so a more efficient heat transfer when heat carriers are fed with the feedstock for fast pyrolysis [176] [187].

Among various types of screw flights, some are well known for handling sticky and viscous materials (i.e., ribbon and interrupted flights) [173] [188], a 'standard' flight used commonly in various applications was selected to mitigate the risk of further challenges in fabrication stage. The pitch to diameter ratios of the screw conveyors were specified as 1 since it has been commonly found optimum in industrial practices [189].

Following multiple configurations and the selection of components, manufacturer benchmark on the standard small auger sizes were consulted [190] from which the relative volumetric capacities to the rotational speed and auger's outer diameter sizes could be predicted. Simply, a single screw diameter (d_o) of 5.08 (cm) allows the conveyance of ~ 9 kg/hr of FS with a density of ρ : 1600 kg/m³ [148], at a screw speed of 1 RPM. Considering the fact that a twin auger configuration increases the throughput capacity by a factor of 1.5, a screw diameter of 2.54 cm could have been potentially suitable. However, the retrofitting constraints on the length of the reactor (1m including motor assembly) and also consultation with an auger manufacturer directed the design towards an auger diameter of 7.2 cm for the twin auger pyrolysis reactor. This could potentially reduce the processing timeframe of stored FS when the throughput is higher. In addition, this auger size provides a chance for heat recycling through the system from the combustion of energy-rich product gases via the hollow shaft to limit the energy intensity of the system in future investigations. Such configuration has been practiced stabilising the heat gradient in the reactor via introduction of a heat transfer fluid [186] [191]. Additionally, the larger auger size would allow the sticky FS to flow freely within the unit, mitigates the chance of clogage and is simpler to manufacture. It is notable that the trade-off between the size and screw rotation speed could make the volumetric capacity of the reactor adjustable.

Table 5-2, shows the auger specifications for the twin auger pyrolysis unit and the anticipated volumetric throughput as well as various application constraints for consideration through manufacturing stage. The thermal reactor fabricated is not necessarily compliant with the values specified in the table below since the

manufacturing was pursued with off-the-shelf tubes and equipment. Stainless steel AISI 316 was used for the manufacturing of all components in the system.

Table 5-2 Pyrolysis Unit specifications (derived from auger manufacturing catalogues [190]) and application constraints

Specs	v_c^6 (cm ³ /REV)	d_o^7 (mm)	s_o^8 (mm)	SWT ⁹ (mm)	p_s^{10} (mm)	d_c^{11} (mm)	CWT ¹² (mm)
Twin Auger Pyrolizer	510	~72	30	3	~72	~84	3
Constraint of this application	1	Reactor length should be limited within 1m with the motor configuration (30cm)					
	2	No carrier gases (gas cylinders) could be implemented					
	3	Lowest operational heat fluxes as possible					

The nominal feedstock and product residence times as well as velocities were calculated as a function of the occupied cross-sectional area within the reactor to form an iterative pattern and predict the length of the reactor. Considering the application constraints, fast pyrolysis was considered impractical for the calculations since vapour residence time of <2 seconds is needed for this pyrolysis mode. Henceforth, aiming for a slow/intermediate pyrolysis of human FS, the screw speed was considered as 1 RPM and the cross section of the

⁶ V_c : Volumetric capacity

⁷ D_o : Screw outer diameter

⁸ S_o : Shaft outer diameter

⁹ SWT: Shaft wall thickness

¹⁰ P_s : Screw pitch length

¹¹ d_c : Casing outer diameter

¹² CWT: Casing wall thickness

reactor was defined as a rectangle to simplify the calculations. Finding the nominal vapour velocity as 3.93 cm/s, an assumption was made on the vapour residence times based on the pyrolysis mode selected, 10-30 seconds [173]. Calculated in the Appendix D, the anticipated vapour exit ports exceed the limitation on the length but since no carrier gases are to be used, the expected gas residence times should be longer. Subsequently, the overall length was assumed as 700 mm with the last exit port placed about 670mm from the centre of biomass inlet delivering a vapour residence time of 17s. However, upon manufacturing the vapour exit ports were perforated with a slight discrepancy from the calculations with last port connected to a nitrogen supply at 611.25mm distance from the centre of feedstock inlet, depicted in Figure 5-3.

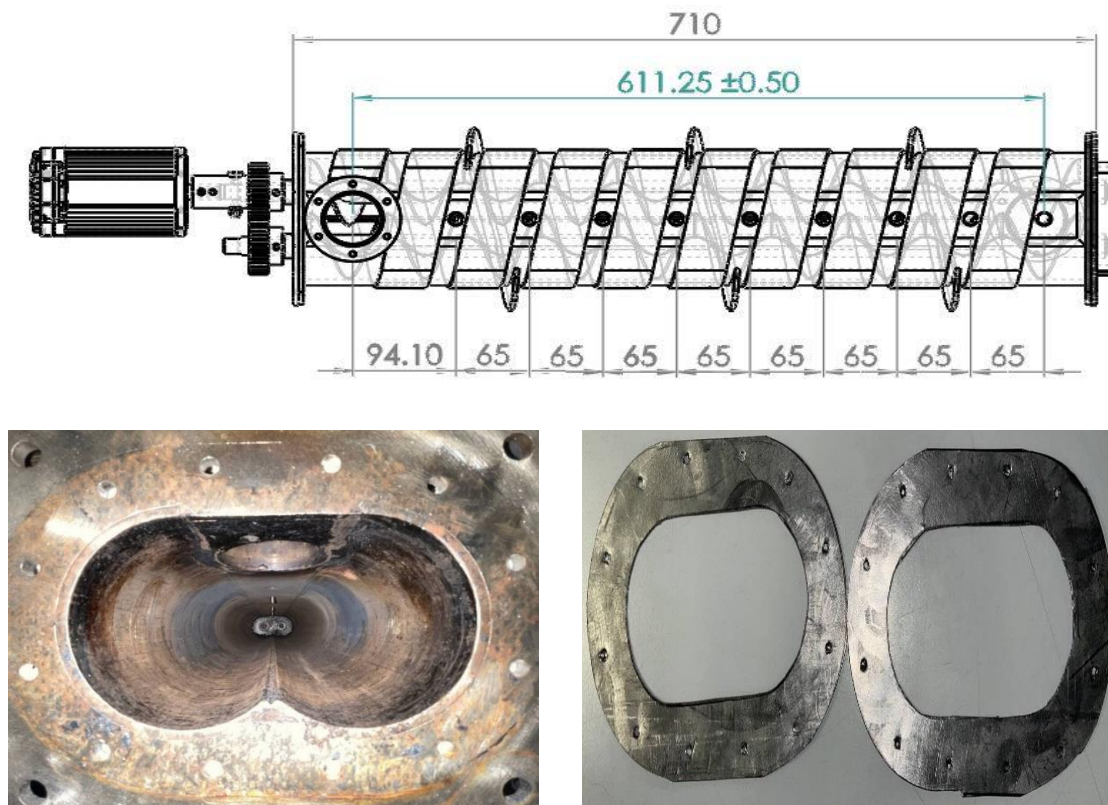


Figure 5-3 Sizing of the twin auger reactor (top) – cross-section (bottom left) and graphite sealings (bottom right)

The twin auger forms a (ω) cross sections with the flights intermeshing about 10mm. End plates on which the bearings were mounted were bolted on the sides of the unit while sealed with two layers of graphite sheet in addition to the gasket

in between the surfaces to somewhat compensate the thermal expansion in the shaft at high temperatures, Figure 5-3. The gas exit ports drilled as a part of modular design which remained unused were shut with screw bolts during rig commissioning.

It is notable that the vapour residence times in auger reactors are typically independent of the screw speed and the solid residence times. The described calculations do not consider the function of heat transfer on vapour residence times and also the filling level of solids within the unit tend to complicate the determinations. The specified vapour exit ports each have a diameter of 12.7mm.

In order to predict the heat transfer mechanisms within the reactor, some assumptions were made on the required heat for the pyrolysis (enthalpy) which includes the sensible heat and the heat of pyrolysis, detailed in Appendix D. The heat for pyrolysis of various biomass and waste materials has been investigated in the past, ranging from 0.7-8 MJ/kg depending on the fuel type and the moisture contents [192]. In the case of sludge materials, an enthalpy of 0.7 MJ/kg was determined [116]. In this study, an initial 3 MJ/kg was selected as the enthalpy value since it was assumed that a fuel with ~15% moisture content could be suitable for the pyrolysis [109], whilst the specific heat capacity of the sludge was noted as 4 kJ/kg.K [193]. A review of the literature revealed the use of various type of heaters and different heating powers depending on the required mode of pyrolysis for the application [194] [179].

5.2.2 Setup and commissioning

Three 940Wh flexible heating tapes were wrapped around the reactor considering the power levels available on the train, to gradually increase the sludge temperature throughout the tube length. To measure and control the temperature within the reactor, K type thermocouples were fixed on gas/vapour exit ports and connected to separate PID controllers to maintain a constant temperature at different zones of the unit, illustrated in Figure 5-4. The whole reactor tube and the piping were insulated with 25mm (thickness) ceramic fibre blankets to minimise heat dissipation or condensation of products.

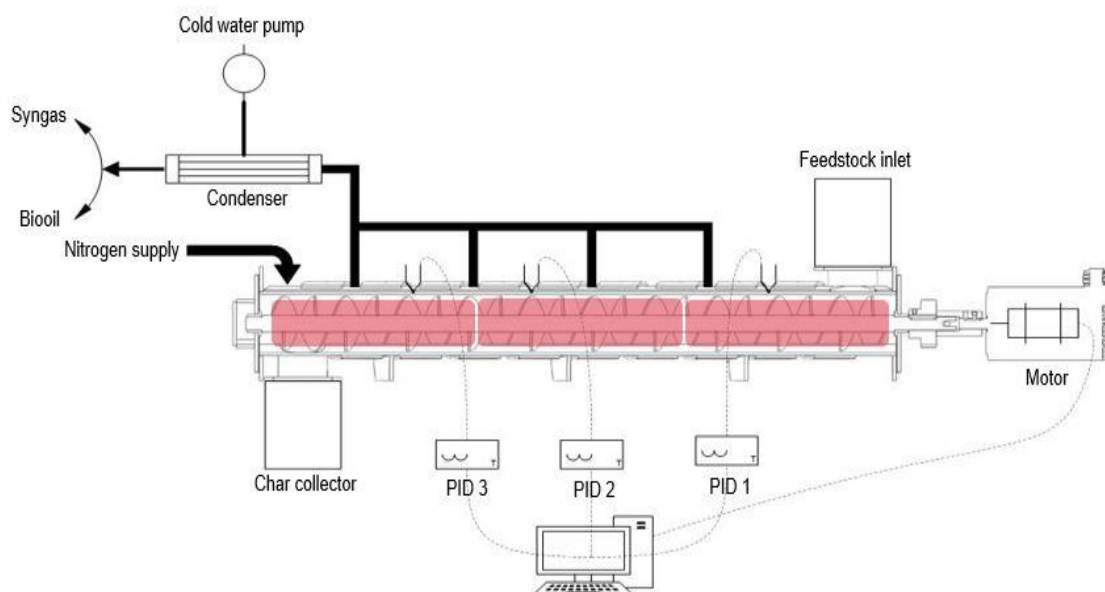


Figure 5-4 Side view of the twin auger pyrolysis unit and the instrumentation

Through a novel design for the lab testing of the unit, a vertical hopper (cylinder) having two sliders on the top and bottom was bolted to the feedstock inlet. The sliders reduced the chance of air ingress within the reactor during operation while the feedstock entered the reactor via gravitational forces.

Prior to the commissioning, in order to obtain an insight on the achievable solid residence times respective to the screw speed (RPM), multiple cold flow tests with partially dried FS were conducted, Figure 5-5. Typically, solid residence times for slow/intermediate pyrolysis are known to improvise around 8 minutes [6]. Thus, to narrow down the tests plan due to feedstock shortage, pyrolysis efficiency at varying temperatures with a residence time of ~12 minutes was solely conducted in this study.

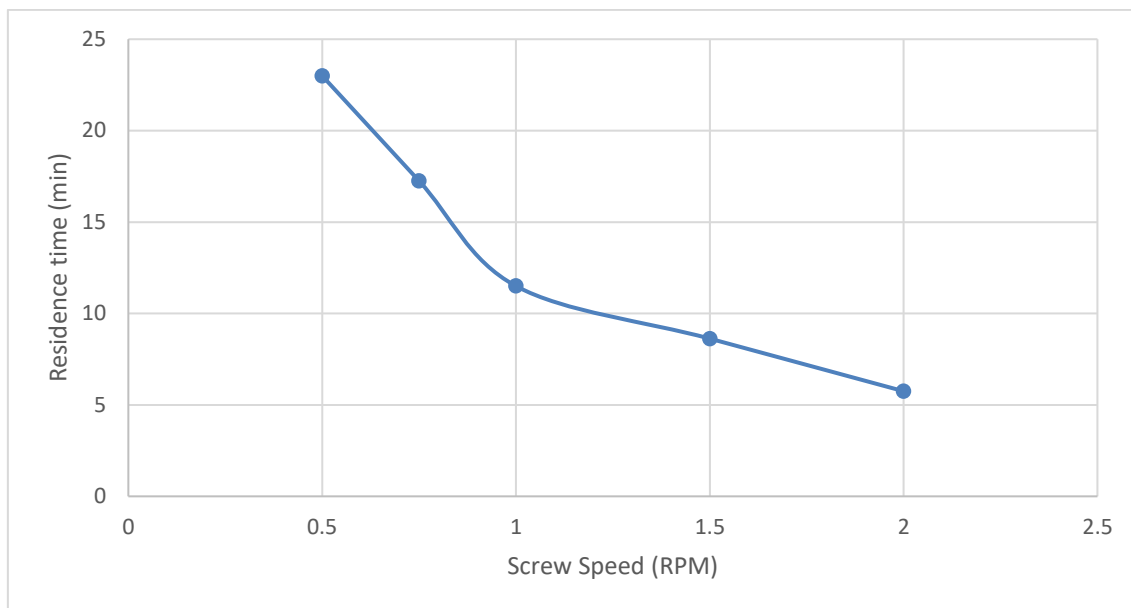


Figure 5-5 Faecal sludge residence times at different screw speeds of twin auger pyrolizer

For the commissioning of the unit, the reactor was inclined 5° upwards toward the outlet to prevent the water from tripping into the char chamber. Furthermore, it was purged with 3L of nitrogen for 1 hour while the lower slider of the hopper was shut to evacuate the present air/oxygen through unit dismantling. Meanwhile the unit was heated up to a desired temperature and allowed for a steady heat profile, Appendix E. The partially dried feedstock was poured into the hopper and the top slider of the hopper was shut. Prior to opening of the bottom slider, the nitrogen purge was terminated, and the motors turned on. Each test lasted for 20 minutes to ensure the complete processing of FS from the hopper and the emptying of char from the unit via mechanical conveyance.

5.2.3 Pyrolytic product's analytical methods

Collection chamber was fixed on the outlet to collect the char at the end of each experiment. The gaseous products from the pyrolytic degradation of FS exit the reaction area using four pipes adjusted along the tube and pass through a stainless-steel condenser. At this point, the non-condensable fraction was collected in 3L Tedlar gas bags while the condensable hydrocarbons enter a large

vessel fitted at the bottom of the condenser. The condensation tower was dismantled after each experiment and rinsed with plenty of acetone and de-ionised water and further dried in an oven overnight at 90°C.

Following the successful completion of each test, the syngas collected in gas bags was analysed for the content of combustible fractions and their yield was determined by the subtraction of biooil and biochar from 100%. 9ml of gases was dispensed in a syringe and three repetitions, each 3ml, were injected into an Agilent 990 micro gas GC operated by SOPRANE II. The device contained two modules, MS5A SS 10mm*0.25mm*30um and a PoraPLOT Q UM 10m*0.25mm*8um heated at 80°C and 60°C respectively. Quantification of the chromatogram peaks were completed using standard calibration gas mixtures of 0.02%, 0.2% and 1% containing CH₄, CO, C₂H₆, C₃H₈ and H₂ as well as CO₂. Energy content of syngas mixture was then calculated (assuming the selected species contribute to the 100% of the syngas fraction), using the data on the theoretical data on the calorific value of various gas species available in literature [195] [94].

Biooil samples were weighed and the qualitative analysis of the light and heavy fraction of the biooils were performed using a coupled Clarus 680 GC – Clarus SQ8 MS from Perkin Elmer simultaneously. The chromatographic column used was a ZB-WAX (L=30m, ID=0.25mm) from Phenomenex suitable for polar materials with high purity grade helium as the carrier gas (1 mL/min). Similar to the method outlined by Gaojin et al. (2015), about 200mg of biooil was dissolved in 5ml of acetone and almost 3g of anhydrous sodium sulphate was added to the mixture for dehydration due to the high moisture content of the feedstock [196]. The mixture was then filtered and 1 µL was automatically sampled and injected in inlet heated at 245°C. The oven temperature was programmed as following: hold for 2 minutes at 50°C followed by ramp up to 90°C at 10°C/min without holding and then temperature increase to 120°C/min at 4°C without holding followed by ramp up to 230°C at 8°C/min and hold for 10 minutes. The mass spectrometer's (MS) source was kept at 230°C with the mass selective detector operating in electron impact (EI) ionisation mode at 70eV.

The reactor was allowed to cool down and the solid char was weighed and analysed for their calorific value (HHV) after drying at 105°C for two hours. The washings from the bomb calorimeter were analysed for the content of inorganic anions using a Dionex ICS-1600. To understand the proximate properties of the char, thermal gravimetric analyses were performed using a TGA8000 from Perkin Elmer. Similar to the method outlined by Saldarriaga et al (2015) for proximate analysis with TGA [197], the temperature program used for this analysis was as following: switch the purge gas to nitrogen at 60 SCCM and Hold for 1 minute at 50°C following which the furnace was heated to 105°C at a rate of 30°C/min and hold for 30 minute for complete moisture evaporation, then the temperature was raised to 700°C at a rate of 30°C/min and held for 30 minute for the volatiles to be driven off, then the purge gas was switched to air at 60 ml/min and held for another 15 minutes for the complete combustion of the samples and determination of fixed carbon and ash content. Lastly, the content of C, N, H were determined using an elemental analyser from ELEMENTAR. The content of oxygen was determined by subtraction from 100%.

5.3 Results and discussion

TGA analysis on the faecal sludge samples in an earlier study showed the maximum degradation point for the faecal sludge samples improvising around 375°C during the slow/intermediate pyrolysis modes. Hence, together with the findings in our earlier study on the suitable temperature ranges favouring the production of high-quality syngas through the pyrolysis of different biomass and wastes [6], the newly built unit was tested at three temperatures of 375°C, 450°C and 500°C.

The moisture content of the products from the dryer integrated within the ClearTrack system prior to the pyrolysis unit for different feed volumes entering the system through each toilet flush is provided in Table 5-3.

Table 5-3 Moisture content of partially dried products with respect to the masses processed

Feed mass (g)	Temperature (°C)	Residence time (min)	Product moisture content (%)
100	150	~60	53
160	150	~60	66
250	150	~60	70
400	150	~60	72

Analysing the data on the reduction in moisture efficiency of the drying unit, high sensitivity of the dryer to the feedstock masses below 250g was concluded. Moreover, collection of faecal waste from different trains showed lesser volumes of faecal waste than the figures considered for the design and manufacturing of the pyrolysis reactor. In addition, limitations on the sample collection from depots due to COVID-19 situation further restricted the test plan. Hence, to facilitate the testing of the pyrolysis unit with limited feedstock volumes, batches of 100g/cap/day and 250g/cap/day of raw faecal waste for 3 persons were passed through the drying unit and the partially dried products were further fed into the pyrolysis unit. The selected mass figures for pyrolysis feedstock preparation potentially represent the lowest (A) and highest (B) limits of faecal sludge masses collected from a CET on trains with short and long journeys respectively, Table 5-4. It is notable that the results on the efficiency of the dryer in moisture reduction were not utilised during the fast-prototyping stage of the pyrolysis unit.

Table 5-4 Pyrolysis tests at different temperatures with the feedstock prepared using the dryer

Test set	Test No.	Cap/day	Mass (~)	Total mass (g)	Temperature (°C)	Mass of partially dried feed (g)
A	1	3	100	300	375	52
	2	3	100	300	450	52
	3	3	100	300	500	54
B	4	--	--	--	375	--
	5	3	250	750	450	119
	6	3	250	750	500	123

In addition, the simultaneous effects of feedstock flowrates and moisture content on the pyrolytic product yields and properties were assessed. The chamber provisioned for the storage of partially dried feedstock prior to pyrolysis, enables an alternative operational frequency for the pyrolizers retrofitted on different trains.

5.3.1 Product distribution

The yield and distribution of products from the pyrolysis of feedstock prepared in test set A are provided in Figure 5-7. The syngas yield curves were normalized by the subtraction of the wt.% of char and biooil from 100 wt.% of feedstock. Completing the first test at 375°C (test 1), due to shortage of raw faecal sludge and the incomplete conversion of the char shown in Figure 5-6, no further test at this temperature (test 4) was conducted. The weight percentages for the biochar, biooil and syngas fractions obtained from test set B changed from 12.67% to 11.50%, 54.89% to 52.71% and 32.43% to 35.79% respectively, with an increase in the processing temperature from 450°C to 500°C.



Figure 5-6 Incomplete conversion of char obtained from test 1 at 375°C

Increasing the process temperature favoured the production of more biooil up to 450°C in both sets of tests after which it declined due to occurrence of secondary reaction during which organic bonds are cracked [198] [104] [199]. Maximum yield of condensable fraction for the lowest (A) and highest (B) moisture content and mass of waste was 50.13% and 54.89% at 450°C operating temperature of the reactor respectively. It is notable that the residual biooil in the condensation tower (not obtainable through decanting) were not accounted for in these analyses. Meanwhile, the syngas yield observed an upwards trend at higher temperatures than 450°C with a greater shift in the case of feedstock with higher volume and moisture content.

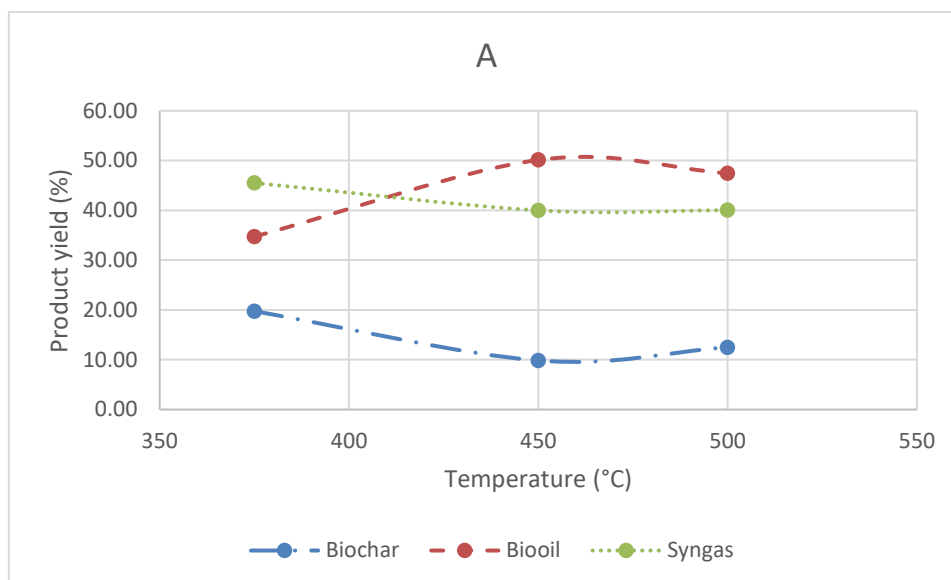


Figure 5-7 Pyrolysis product's distribution (Test set A, described in Table 5-4)

It is known that the higher water vapour partial pressure in the reaction area contributes to the production of more syngas significantly through steam reforming of the volatiles with the catalytic help of the char [200]. However, the rate of syngas yield stayed insignificant at higher temperatures in this study since the volume of feedstock was also increased with moisture content. The escalation of feedstock flowrate enhanced the production of more biooil in a study on the pyrolysis of sawmill residues in an auger reactor enabling shorter vapor residence times as a result of higher vapour volumetric flowrate within the reactor [104]. In addition to lesser cracking of condensable fraction in the reactor, the biooil deposition in the pipeline is depleted resulting in higher yields of liquid.

To conclude, the overall difference in the yield of products is negligibly altered comparing the tests in test set A and B. Investigating the effects of feed flowrate during fast pyrolysis of biomass showed minor influences on the yield below 1.92 kg/h due to adequate heat transfers through reactor wall to the feedstock [201]. The ClearTrack pyrolysis unit has pipes installed throughout the tube boosting the evacuation of vapours from reaction area. Hence, the yield of biooil remained

dominant in all the tests as a result of higher volume and moisture content of the feedstock.

Similar to other research on the pyrolysis of biomass and sludge feedstock, the char yield decreased when the processing temperature climbed up [202] [84]. The formation of char remained lowest due to the small content of ash in the faecal sludge feedstock (4 – 7 wt.%). High ash content and nutrients are commonly known to catalyse the char/coke formation [203]. Operating the unit at 500°C in both test sets A and B, the yield of char remained higher in the former set, potentially due to longer vapor residence times, when feed flowrate is lower, leading to repolymerization of volatiles and further formation of char [204].

5.3.2 Syngas

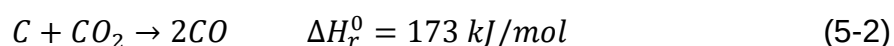
Table 5-5 includes the calculated concentration of syngas species for the feedstocks prepared and thermally converted at different temperatures outlined in Table 5-4. Results confirm the dominant presence of CO₂ followed by CO, CH₄, H₂ and C₂ – C₃ species. Enhanced production of CH₄ was observed with temperature escalation, a result of thermal cracking reactions, ranging up to 6.7 mol% and 10.5 mol% for A and B at 500°C respectively. Similarly, a study on the pyrolysis of human faeces at low heating rates highlighted the maximum evolution of 35% methane at 500°C [130]. CO₂ observed a downwards trajectory once the processing temperature was increased to 500°C, reducing almost 5% and 8% in A and B test sets. The peak concentration of CO was at temperatures lower than 400°C ranging up to 31.4% in set A decreasing almost 5% at 500°C.

Table 5-5 Pyrolysis gas composition and energy content under slow/intermediate processing modes

Test set	Test No.	Gas composition (mol%)						CV
		CH ₄	CO ₂	C ₂ H ₆	C ₃ H ₈	CO	H ₂	MJ/Nm ³
A	1	1.0	48.8	0.3	0.6	31.4	2.0	5.4
	2	4.4	43.8	1.2	0.3	25.1	4.9	6.6
	3	6.7	44.4	2.1	0.2	27.7	8.8	8.9
B	5	5.9	44.3	2.0	0.3	25.5	1.5	7.4
	6	10.5	35.7	2.6	0.1	25.2	3.6	9.7

Typically, CO and CO₂ are products of cellulose and hemicellulose decomposition while CH₄ and H₂ are attributed to the breakage in lignin fraction [205]. The comparative results observed for the CO₂ and CO are not in line with those confirmed for horse manure where CO is found to be the most abundant [202]. Analysis on the pyrolysis of sewage sludge in a tubular reactor has also shown an enhanced CO production alternating the temperature from 450°C – 650°C at the cost of CO₂ with the following reaction [198]:

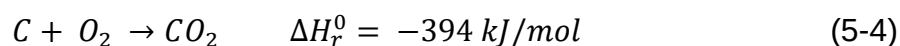
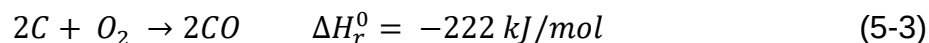
Reverse Boudouard reaction



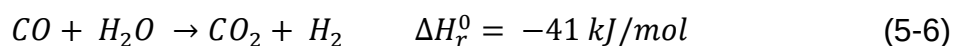
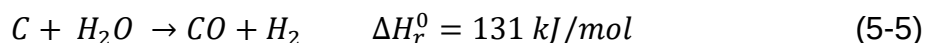
It is notable that the combined effects of process parameters also contribute to the evolution of these species complicating the result interpretation. Most researchers explore the effects of process parameters individually with a few ones investigating the interactions between process variables [204]. In this study, the dominance of CO₂ and CO are primarily attributed to the chemical properties of feedstock containing high C and O fractions followed by the oxidation (5-3) – (5-4), and water-gas reactions (5-5) – (5-6) [206], taking place as a results of air

ingress through the hopper and bearing components of the system and high moisture content of feedstock.

Partial/oxidation reactions



Water-gas/shift reactions



H₂ underwent a surge with higher temperatures up to 8.8 mol% and 3.6% for the feedstock used in set A and B respectively. However, the concentration of H₂ was significantly reduced once the feedstock flowrate and moisture content were increased in set B. Commonly reported, H₂ generation is almost doubled between temperatures of 700 – 1000°C while the higher moisture content in the feedstock is known to promote the occurrence of secondary reactions boosting H₂ production [200] [84] [207] [99]. The depletion of H₂ in a comparative analysis between set A and B implies the impacts of higher feedstock flowrate overtaking those from higher moisture content and processing temperature. The upsurge in the vapour pressure and flowrate within the reaction area shortens their residence times and consequently reduces the chance of secondary reactions (e.g., steam-methane reforming reactions) for higher hydrogen production [202].

Analysis on the C₂ – C₃ fractions showed an opposite evolution behaviour with temperature escalation which was negligible and thus not discussed in this study. Meanwhile, the discrepancies with the overall volume of gases detected (~80%) in all tests is neglected in this study. Quantifying the results, the calorific value (CV) of the syngas mixture increased with higher temperatures mainly due to higher CH₄ and H₂ contents.

5.3.3 Biooil

Qualitative analysis of the biooil samples obtained from the intermediate pyrolysis of faecal sludge indicated a large number of oxygenated compounds similar to the findings in literature [196] [208]. The software (Turbomass) was programmed to generate a report with the 30 of the largest peaks detected in each chromatogram having relative area >0.5% listed in Appendix F. The identified compounds occupied only 50 – 60% of the total biooils implying their complex composition. The rest of the compounds could potentially be detected through enhancement of the rudimentary GCMS method utilised except the non-volatiles which are not detectable by GCMS.

Increasing the temperature in both test sets, a larger group of compounds were detectable with the same GCMS method. Meanwhile, comparing the biooil composition from test sets A and B showed a reduction in the total RPA¹³ (%) concluding the presence of larger molecules with heavier molecular weights in the biooils from latter test set which remained undetected. Typically, an increase in the feed flowrate results in shorter residence time for the gas phase in the reactor and lessens the production of light weight hydrocarbons through secondary cracking and repolymerisation of volatiles [209] [210].

¹³ RPA: Relative peak area

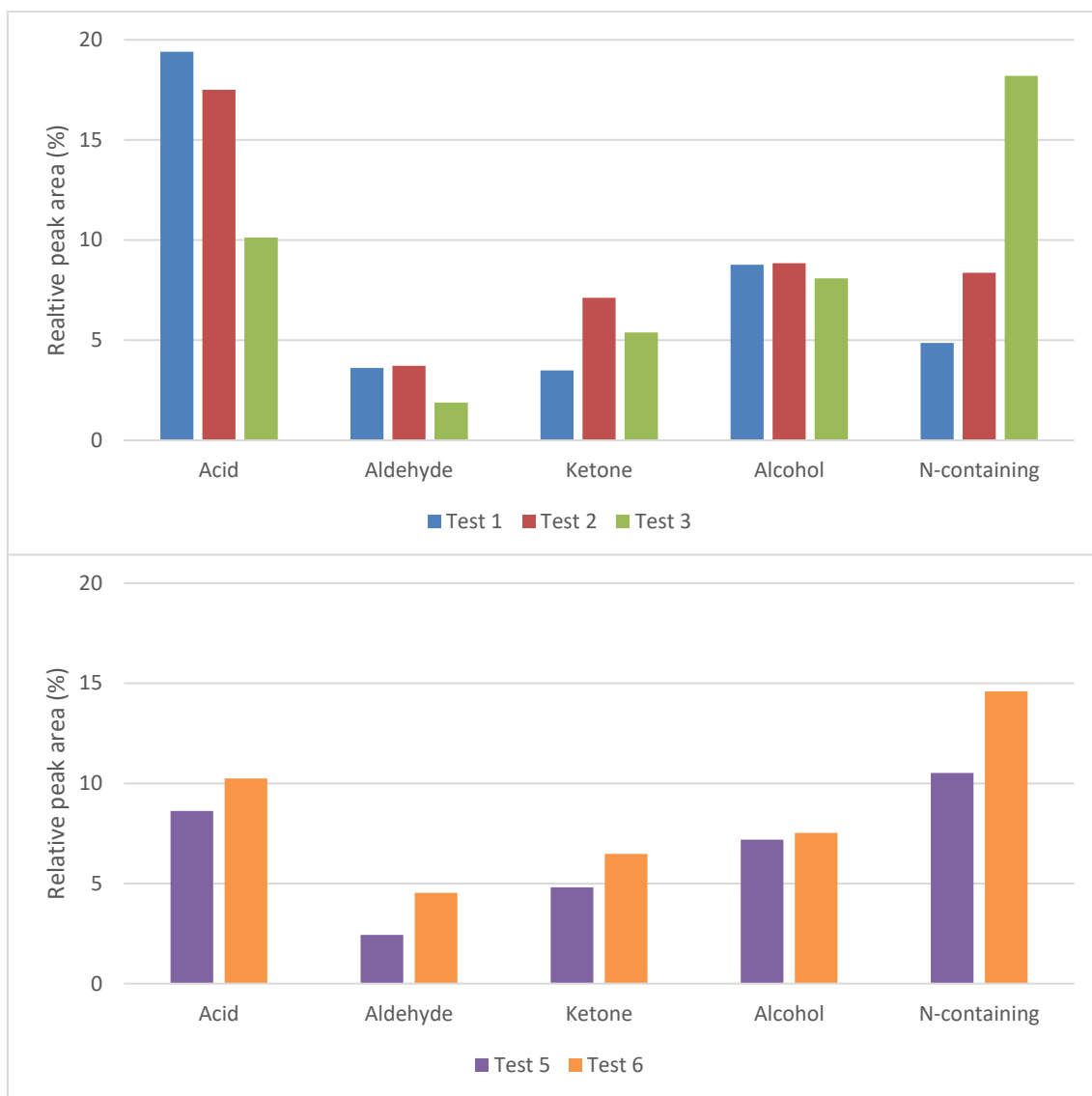


Figure 5-8 Major hydrocarbon species in biooil samples from pyrolysis tests in test sets A and B

The most abundant species (RPA>1%) in all biooil samples are summarised in Figure 5-8 showing the dominant presence of acidic components followed by N-containing hydrocarbons, alcohols, ketones and aldehydes. Results indicated acetic acid as the principal acidic component in biooil from test 1 reducing with the overall acid concentration when temperature was raised to 500°C. These findings are in line with the observations in a study on the fast pyrolysis of rice husk in a conical spouted bed reactor where temperature escalation increased

the phenol concentration at the cost of lesser acids and ketones [211]. In contrast, pyrolysis of sewage sludge with the same reactor, yielded lower oxygenated compounds with higher temperatures as 600°C except acids which maximised at 500°C [212]. Increasing the feed flowrates and moisture content (~17%) of the feedstock in test set B, yielded a totally lower abundance of oxygenated compounds similar to a study by Qureshi et al. (2021) on the pyrolysis of palm shell at 500°C at different feeding rates [213].



Figure 5-9 Biooil from test 6 containing high-water content with solubilizing acids, alcohols and ketones from carbohydrate decomposition [214]

The significant concentration of N-containing species in biooil from sludge materials is due to the dehydration reaction of peptide bonds in proteins which contribute to NO_x emissions in combustion applications, thus requiring removal [208]. Depicted in Figure 5-8, N-containing compounds underwent a surge increasing the temperatures to 500°C in both test sets. In a study by Jaramillo-Arango et al. (2016), the aliphatic and aromatic hydrocarbon concentrations from sewage sludge pyrolysis in fluidized-bed reactor reduced while the nitrogen-containing compounds climbed up at higher temperatures up to 800°C [199]. It is likely that, the effects of temperature on the evolution of N-containing compounds

in this study have overtaken the opposite influences of moisture content and feed flowrate in a comparison between biooil composition in set A and B [213]. Mei et al. (2020) reported a drastic reduction of N-containing compounds once the fuel's moisture content exceeded 20.57% [200].

5.3.4 Biochar

Chemical properties of the biochar derived from the pyrolysis of faecal sludge samples are summarised in Table 5-6. The volatile matter content of the pyrolytic solid residues reduced 61% and 40% in test set A and B respectively, in a positive correlation with their calorific value similar to other studies on the production of biochar from human manure [215]. The reduction of calorific value in biochar at higher processing temperatures could also be attributed to the higher ash contents of biochar samples containing 24% and 32% more ash in comparison to their parent faecal sludge (5 ± 3 wt.%, dry basis) [208]. This is a unique feature in the biochar made from sewage sludge in contrast to those of biomass materials resulting in higher ash contents with the increasing temperature due to significant retention of inorganics in the biochar matrix [216] [217] [218].

Table 5-6 Chemical characteristics of the biochar residues from the pyrolysis of faecal sludge

		Test Set A			Test Set B	
		Test 1	Test 2	Test 3	Test 5	Test 6
arb%	Mc	2.26	2.66	3.12	1.42	1.46
Dry basis %	V _M	31.43	22.18	12.08	17.25	10.36
	F _C	44.23	49.27	58.45	46.46	52.57
	Ash	24.33	28.53	29.46	36.27	37.05
	C	47.48	47.99	49.84	52.81	52.63
	N	1.88	1.96	2.05	2.37	2.55
	H	4.83	3.47	2.76	2.81	2.29
	O	45.81	46.58	45.35	42.01	42.53
ppm	Cl	6272.26	6067.78	11029.72	4966.42	5484.76
	S	895.43	558.12	514.44	558.68	515.63
	P	6336.84	5886.04	3215.63	4610.68	3998.98
mg/L	NO ₃ ⁻	467.43	295.21	198.97	312.57	272.36
	NO ₂ ⁻	2.9067	6.15	2.04	5.18	5.89
HHV (MJ/kg)		22.17	21.68	21	20.29	19

The calorific value of the resultant char (20 ± 2 MJ/kg) remained close to that of human faeces and sewage sludge [219] [170], but was lesser than biomass derived chars [213]. The high fixed carbon content of the biochar makes them attractive for contaminant removal such as H₂S in adsorption applications [220] [221]. Comparing the carbon content of biochar in between experiments in set A

and B, the insignificant effects of secondary reactions (5-2)(5-4)(5-5), in comparison to temperature can be concluded. Mosko et al. (2022) reported a significantly lower carbon content for the biochar obtained from the pyrolysis of sewage sludge in quartz reactor at higher temperatures up to 800°C conducted under purge gas with 70 vol% water content due to reverse Boudouard reaction [222]. In Cleartrack pyrolysis unit, the gases exit the reaction area immediately reducing the further chances of char-gas interaction.

Finally, significant retention of chlorine in the biochar was observed while the content of sulphur and phosphorus reduced to almost half when the temperature was raised from 375 to 500°C in test set A. The high contents of chlorine observed with the biochar obtained from test 3 could be attributed to potential use of bleach for toilet cleaning or other sources.

5.3.5 On-board or off-grid utilisation of products

Unlike the other thermochemical conversion processes, pyrolysis delivers multiple products that need to be handled properly due to the presence of various inorganics and toxic elements as well as heavy metals in the solid biochar and biooil fractions [218] [223]. The main use of the syngas on-board the train can be for the immediate combustion and energy recovery since their storage is not possible due to safety issues. In addition, the biochar fraction can be used for energy recovery purposes. However, the exhaust of such a combustion process will need further emission controls to limit the concentration of pollutants below regulative figures for toxic and hazardous elements. For the off-grid use of the biochar as fertilizer, further analyses on the contents of heavy metals and nutrients would be necessary to meet certain standards [223]. The effects of process parameters on bio-oil composition are extensively investigated for different biomass and waste materials individually with a few ones exploring the simultaneous impacts. It is notable that, reactor design plays a key role on biooil composition in parallel to other process conditions [209]. Thus, it is essential to identify the end-use application of biooil before planning any reactor configurations to maximise the quantity of various desirable species. In the case

of off-grid utilisation of biooils from this process, phenols can be used as low-cost renewable resins, ketones are suitable biofuel compounds forming esters upon oxidation, organic acids upon fractionation could be used for the production calcium salts, an environment friendly road de-icer and aldehydes are a potential renewable fuel for fuel cells [224] [214] [225] [226]. For the recovery of energy contained within biooil, production of furans, phenols and cyclopentenone are of favour ensuring a good combustibility of the biooil [227]. It is notable that the biooils generated in this research are predicted to contain high water contents which makes them unsuitable for combustion purposes.

5.4 Conclusion

A novel micro-scale twin auger pyrolysis reactor for the conversion/stabilisation of highly wet sanitary faecal sludge generated in on-board train toilets was designed and successfully commissioned. The innovative configuration of twin auger aimed for the maximum solid reduction through rapid vapour removal in the shortest processing timeframe. This design pursued the maximum volume reduction ($\sim 88\% \pm 1$) of waste to biochar up to 500°C with the immediate evacuation of hydrocarbon vapours from reaction area using no carrier gas to limit volatile repolymerisation. The low energy content of the syngas ($\sim 8 - 9$ MJ/kg) implied the need for a prolonged residence time of solid and gas phases within the reactor to promote the production of higher calorific value syngas for limitation on energy consumption upon its recovery. However, in parallel to the effects of process parameters (e.g., temperature and feed flowrate), the importance of reactor design and configuration on the existing trade-off between the yield and composition of product biofuels was highlighted in this study.

Extending the residence times, more biochar could be yielded while the longer chain oxygenated compounds break into lighter weight species. Acids and N-containing species formed the most abundant hydrocarbon species (~ 10 and 17% respectively) in the obtained biooils at 500°C . Typically, direct use of the biooil is impractical due to their high-water content which on the contrary facilitates their transportation due to promotion of lower oil viscosities enhancing

their flow properties in burners and atomizers. It is essential to identify the end-use of the pyrolytic products prior to any application for a better design and configuration of the reactors. The biochar contained ~58% fixed carbon confirming suitable adsorption properties. The concentration of nutrients such P and contaminants (Cl and S) should be evaluated according to the existing regulatory limitations for thermal processes.

For future work, further tests for a better understanding of feed flowrates in the real-world scenario are favourable. Assessment on the effects of fuel with other moisture contents is necessary whilst the reactor design implications could be planned ahead according to the fate of pyrolytic products.

Chapter Six

6 Research Conclusions

This Chapter collates all findings from this research project and elaborates further on the scientific significance of this work. It discusses the overall contribution to knowledge highlighting the novelty and the potential impact of this PhD research. Recommendations for future research are outlined.

6.1 Introduction

The main aim of this PhD project was to develop and evaluate a novel thermal treatment system in micro scales for rolling stock suitable to manage hazardous faecal sludge. The innovative system required to render the frequent and robust conversion of sludge for the maximum volume reduction of solids.

Throughout this research project, a systematic development of a novel thermal treatment system for rolling stock has been carried out. Each Chapter contains distinct discussion and conclusion sections. Following the conclusions from each Chapter, the work package for the subsequent Chapters were defined and further investigated. In this Chapter, a summary of the overall findings in this thesis is provided and the levels of success as well as research limitations are discussed. The contribution to knowledge of the objectives investigated are highlighted and the significance of the work is covered.

6.2 Overview of the Research

The overall aim and objectives were set out in the Chapter 1 of this thesis. The work package covering each of the objectives are described and discussed below:

- 1. To conduct a critical literature review on the application of thermal processes in commercial and small scales to select a suitable technology for ClearTrack application. To identify the process constraints and discuss the requirements for technology implementation and how the challenges could be addressed.*

The widely utilised sewage sludge stabilisation and management methods in conventional wastewater treatment plants were comprehensively discussed in Chapter 2. The associated operational challenges with the physiochemical properties of the feedstock are critically covered and the eligibility of each technology is discussed. It was concluded that pyrolysis technologies can perform best considering the presence of very high moisture contents and inorganic contaminants in the sanitary sludge. This resulted from the findings in various studies where significant retention of heavy metals and inorganics occurred in the solid biochar. Also, lesser sensitivity of pyrolysis to the fuel's moisture content in comparison to other thermal processes was concluded. The need for ignition in the two latter technologies urge the use of auxiliary fuels for a consistent conversion of waste feedstock which is infeasible in ClearTrack application. Furthermore, very high temperatures involved with the ignition of the fuel in these processes led to the malfunctioning of the prototypes, burning the fuel and consequently clogging at the reactor inlet. The effects of process parameters on the pyrolytic product's yields and properties were covered and discussed to understand the best operating conditions for a pyrolysis technology built for such applications. Meanwhile, the best operating conditions was concluded as the delivery of products suitable for immediate energy recovery to limit the energy consumptions as the main concern over advanced thermal processes. The overall conclusions of Chapter 2 highlighted pyrolysis as an area for further research.

- 2. To carry out the complete chemical and thermal characterisation of the faecal sludge generated in on-board toilets to understand the properties of the feedstock as well as their kinetic behaviour.*

Using the knowledge gained from Chapter 1, the thermochemical conversion characteristics of multiple batches of waste collected from different controlled emission tanks (CETs) were analysed. Proximate and ultimate properties and the energy contents of the waste entering the pyrolysis system were determined in Chapter 3. Following this, the pyrolysis conversion of human faecal sludge (HFS) was conducted with thermogravimetric analysis (TGA) to understand their degradation behaviour and provide an insight into the kinetic parameters, e.g., activation energies and frequency factors. Meanwhile, the pyrolysis reactions could be defined with first-order irreversible reactions. However, further analysis on the waste from CETs on other trains with shorter/longer journeys are suggested which are predicted to be different due to alternative frequencies of defecation.

3. *To develop a novel drying unit for the reduction in moisture and volume of sludge prior to final stabilisation as well as nutrient recovery.*

Findings in the Chapter 2 and 3 of this research study revealed the need for the removal of moisture from sludge materials. In the case of pyrolysis, removal of moisture (pre-treatment) from biomass and waste has been mainly to deliver high-energy content biooil product, the desirable fuel from pyrolysis of biomass and fossil-derived polymers for energy and chemical industry. However, during sludge treatment processes from a wastewater treatment point of view, reduction in the volume of the hazardous waste and the recovery of nutrients through drying technologies are most favoured. In Chapter 4, a newly built single screw drying unit was commissioned and the effects of various process parameters were assessed. Regarding the drying process, residence times of HFS and the operating temperature of the unit were concluded to be the core parameters. However, feedstock flow rate (FFR) as the key application constraint further complicated the optimisation of the unit. An optimised process for the drying of HFS was concluded as a residence time of ~60 minutes at temperatures of 150°C considering all the constraints. Meanwhile, the negligible reduction of carbon in the partially dried HFS were observed and the flush of nutrients in the dryer condensate were fully discussed.

4. *To design and evaluate the thermochemical process of an innovative pyrolysis reactor.*

In Chapter 5 of this thesis, an innovative twin auger pyrolysis unit was engineered for the final conversion and reduction of hazardous faecal waste. Using the knowledge and data on the physiochemical properties of raw sludge and the partially dried feedstock obtained in Chapter 3 and 4 of this research, the pyrolysis reactor was commissioned. Assumptions on the FFR were made and the partially dried feedstock prepared with the dryer was fed into the thermal conversion reactor. The effects of multiple process parameters (e.g., high heating temperature (HHT), moisture content and FFR) were assessed and discussed individually and simultaneously in two sets of tests namely A and B. The assessment was pursued through complete analysis and interpretation of the distribution and properties of the product fuels from the pyrolysis reactor with the biooil forming the abundant fraction on wet basis. Higher temperatures of 500°C led to the generation of higher quality syngas fractions (CV: 10MJ/Nm³) while reducing the char to almost 10% by weight. It was concluded that the alteration of FFR and consequently the moisture content of feedstock had significant impact on the properties of the products but not their yield. Reactor design and configuration played a key role together with the feedstock flowrate (FFR) and HHT on the extent of hydrocarbon species in the biooil while the impacts variation in moisture content (20 wt.%) was overtaken by the former process parameters in most tests. In Chapter 2 of this research (published) a novel system is discussed to be capable of generating products for simultaneous combustion and energy recovery to limit the energy consumptions of such system. Utilising a pyrolysis system for such applications, the syngas and biochar fractions could be directly combusted but the biooil, similar to other studies, cannot be used for energy applications. This is primarily due to the very high-water content of this fraction sourcing from the initial feedstock moisture content and the water formed during the pyrolysis conversion. However, presence of water enables lesser viscosities for the biooil and facilitates its transportation in the pipelines with lesser deposition due to its sticky nature. A longer residence time for the gas and

solid phases were concluded to be of favour for such systems to maximise the generation of syngas with higher calorific value as a result of breakage in longer chain hydrocarbons. This would also lead to the repolymerisation of volatiles and deposition of carbon in the solid phase and formation of more char with higher fixed carbon contents capable of preserving more inorganics, all at the cost of biooil. Regarding the operating temperature, HHTs could potentially accelerate the formation of energy-rich species in the biooil, but this is practically disadvantageous for such systems maintained infrequently.

6.3 Limitations of the research

Completed objectives within this thesis included several limitations, one of which is the volume of sludge, number of CETs and the types of trains from which the samples were collected. During the completion of chemical characterisation tests in Chapter 3, the samples were collected from one depot providing service to one rail operator (Chiltern Railway). Most of the trains in this depot performed journeys with several stops in between the start and destination points which implied the lower chances of defecation in the on-board toilets. For such waste materials, it is vital to understand the properties of a range of waste materials with different heterogenous mixtures for a better prediction of system input and output. In addition, collection of the waste samples was done with containers that in some cases were filled up emptying multiple CETs in them. Not only the volume of HFS on various trains are different but also, the volume of waste generated in each toilet differ where carriages with more passengers had higher content of solids in the CET. Lastly, despite the efforts for sample collection from trains with a more frequent depot visit, microbial degradation of the samples were inevitable. To elaborate on this, later batches of waste collected for analysis in Chapter 4 and 5, were from a different depot during COVID-19 period and the train schedules were not checked.

In Chapter 3, use of other kinetic models has not been investigated. A single method (DAEM) was utilised to provide information on the kinetic properties of HFS for the production of prediction models and understand their degradation

behaviour. However, further development of the model for additional validation of DAEM through calculation of $f(E)$ values and prediction of conversion rates was not investigated and requires further work.

In this thesis, it has been mainly aimed to highlight the evolution of organics and inorganics within such system for the first time to better understand the emissions or discharge from the system. However, lack of regulations on the emissions from thermal processes in the context of small-scale wastewater treatment systems further limits the investigation into the desirable performance of the system. For example, the optimum thermal drying conditions of HFS needs to be assessed taking the efficiency of an effluent purification system into account for the retention of inorganics prior to the reuse or disposal of the liquid stream.

In Chapter 3, the nitrogen content of raw sludge was only determined after complete drying of HFS that forces the significant removal of nitrogen compounds from the sludge. Performing a nitrogen mass balance within such systems plays a vital role for the understanding of emissions which is not completed in this study. The transformation of nitrogen contained in the raw faecal sludge should be investigated using the following equation:

$$N_T = N_D + N_P \quad (6-1)$$

In which, N_T is the total nitrogen in the raw faecal sludge, N_D is the total inorganic nitrogen (e.g., Ammonia plus nitrate plus nitrite) plus ammonium, N_P is the summation of the concentration of nitrogen containing compounds in the pyrolysis biooil, syngas and the biochar all of which include the organic nitrogen fraction as well.

The commissioning of the dryer involved escalation of temperature to approximately 200°C in the case of tests at 150°C since the heaters were controlled with PID. This resulted in the emission of carbon from solid residues fouled within the unit and further complicated the interpretation of ion chromatograms for Chloride due to the presence of acidic compounds in the condensate. A better control of the heat profile with voltage regulators within the

dryer could prevent this problem and enables a better prediction of carbon emissions through an analysis on the chemical oxygen demand of the liquid condensate in each test.

The moisture reduction efficiency of the dryer was limited due to the associated sizing constraints for the retrofitting of the prototype on the train. The optimised dryer performed best at 0.2 RPM while the moisture content of the partially dried feedstock did not short fall of ~50 wt.% in the case of lowest feeding rates (100g). Following this, the limited volumes of HFS for the testing of the pyrolysis reactor forced assumptions on the minimum and maximum FFR of the system.

In Chapter 5, the effects of pyrolysis temperature at a constant residence time for the HFS prepared using the dryer in Chapter 4, was studied in test set A and B. At this point, interpretation of the simultaneous effects of FFR and moisture content on products compositions remained limited to a qualitative discussion. In addition, the measurement of water content in the biooil samples was not carried out in this thesis and the product yields were reported on wet basis.

For the analysis on the syngas products from the pyrolysis reactor, the yield of non-condensable fraction was calculated theoretically from the deduction of biooil and biochar from 100%. Limitations were associated with this analysis since minor biochar were remained in the reactor after each test, some of the heavier fraction of biooil stuck in the condensation tower and was further removed rinsing with solvents. For hyphenation analysis, use of gas bags usually involves with discrepancies due to the gas escaping the bag prior to analysis which was probable in Chapter 5. To overcome this issue, utilisation of online gas analysers or installation of hyphenation instruments (e.g., GC-TCD/MS) to the gas outlet could provide real-time accurate results for the concentration of syngas combustible species.

To understand the composition of the biooil samples obtained from tests performed in test set A and B, a GC method commonly used for the hyphenation of hydrocarbons was adopted. As described in Chapter 5, the summation of all the abundance peaks in the chromatograms only revealed 50 – 60% of the biooil

species. The complex composition of the biooil needed further enhancement of the GC method for the identification of hydrocarbon species.

6.4 Future work

Following the findings and conclusions in each Chapter, future work is recommended to enhance the system's performance suitable for various trains.

Understanding the volumes of solid waste generated on trains is necessary to optimise the operational timeframe of the pyrolysis reactors retrofitted under each toilet. For this, the volumes of solid waste in the CETs with respect to the type and journey of the trains should be recorded to generate a benchmark for the minimum and maximum volumes entering the system under each carriage.

Physiochemical properties of the waste generated on other trains should be analysed further. The thermal degradation of the waste and real-time hyphenation/identification of the vapour products using bench scale analytical instruments can obtain further insights into the optimum temperatures and heating rates for the generation of maximum syngas with the highest calorific value. Meanwhile, use of other kinetic models for the description of HFS degradation behaviour can contribute to the development of prediction models for such systems in future.

The novel single screw drying unit developed and tested in this project performed limited in the reduction of moisture as a result of its short length and ineffective mixing of the HFS. For future work, use of twin auger screw conveyors can be recommended to enhance the HFS fluidisation/mixing and consequently the heat transfer through particles. The optimisation of the drying efficiency of the dryer and the useful contents of moisture in the feedstock should be pursued in a compromise with the yield and quality of pyrolysis gaseous products.

The flush of N-containing cations in the condensate from the dryer is another vital topic for further exploration. Through development and testing of the drying unit, ammonium was found the abundant form of N-containing compound in the condensates from HFS drying. However, the number of tests were limited, and

further tests are needed to understand the effects of process conditions on the ammonium and ammonia concentrations. In the context of a small-scale wastewater treatment system, the condensates should undergo further inorganic removal to conform with emission regulations for non-sewered sanitation systems (e.g., BS ISO 30500) for their direct disposal or reuse. To achieve this, performing nitrogen mass balances within the systems are crucial for future studies.

The developed twin auger pyrolysis reactor was tested for the effects of temperature under constraints due to feedstock unavailability. Further research is necessary to acquire knowledge into the effects of other process parameters, e.g., RT, FFR and HHT as well as fuel-associated parameters such as moisture contents, on the product properties. Exploration of these parameters individually enables better prediction of achievable product yields and compositions. In addition, upon completion of substantial number of tests, the simultaneous effects of these parameters could be modelled using methods such as response surface methodology (RSM) for a better understanding of the systems performance.

In Chapter 5, upon the interpretation of the results, prolonged gas residence times were found favourable for an increase in the yield and CV of syngas. This can be investigated through removal of the vapour exit ports close to the inlet of the reactor. Using the data and knowledge, extents of carbon repolymerisation and deposition in the char fraction can be explained considering a trade-off between the yield and quality of the products.

Completing the mentioned research topics, energy intensity of the system in terms of the energy used for the completion of process and the recoverable energy from the by-products as well as emissions can be determined. Meanwhile, decisions on the optimum processing conditions of the unit can be made based on the criteria for the final utilisation or disposal of the products.

6.5 Contributions to knowledge

The research carried out in this thesis presented outstanding contribution to knowledge in terms of the development of a pioneering system for the

management of non-sewered sanitary wastes and also the knowledge acquired about the thermochemical conversion properties of the HFS generated in rolling stock. Such development has not been carried out in the past to the best of our knowledge.

The chemical characteristics of the sanitary solid wastes were analysed for the first time revealing vast data on their ultimate and proximate properties alongside the contents of inorganics within the dried heterogenous HFS generated in rolling stock. Whilst sewage samples have been extensively analysed in other published works, the data within this PhD builds upon this prior knowledge due to the different environments from which the samples were obtained. In addition, the thermal gravimetric experiments revealed the maximum decomposition temperature ranges for HFS samples while the degradation occurred in two steps similar to sewage waste and paper materials. These valuable sets of data contributed to the future research for the advancement of such low carbon energy systems in terms of their design and operational efficiencies.

Analysis on the kinetic properties of HFS using distributed activation energy model showed a robust description of pyrolysis reactions of HFS by first-order irreversible reactions. The kinetic data on the activation energies and frequency factors are useful for the development of prediction models and the simulation of decompositions reactors in the context of energy from waste systems.

One of the very first thermal drying units for mobile applications (e.g., trains) was developed and tested in this PhD thesis. The performance of the system was comprehensively discussed and substantial information on moisture removal efficiencies, emissions and nutrient recovery mechanisms were provided. The overall study highlighted the role of a dryer within the context of small-scale wastewater treatment system and provided implications for further enhancement of the performance of such design and configurations. The study of the evolution of inorganic contaminants in HFS through conductive drying significantly contributes to the design and planning of a complete wastewater treatment system that aims for the reuse or safe disposal of liquid effluent streams.

The development of this innovative pyrolysis system is significant to many industries (e.g., wastewater treatment, oil and gas, transport etc.) since this system enables the continuous and safe management of non-sewered sanitary wastes. This system proved a robust method for the conversion of hazardous human faecal sludge generated in on-board train toilets, reducing their processing timeframe significantly. Extensive volume reduction and complete destruction of hazardous faecal sludge occurred in less than 15 minutes within the pyrolysis reactor, delivering value-added products for safe disposal or utilisation. One such system can also be implemented for the management of oily sludge in petrochemical industry where substantial amount of hazardous wastewater are produced throughout various stages of crude oil explorations (e.g., oil-water separators and refinery product tanks etc.). utilisation of such technologies can improve the stabilisation of the toxically concentrated heavy metals and pollutants in the product char from oily sludge for further recovery, promoting resource efficiency.

In a comparison with the other thermal treatment technologies such as gasification and combustion, this system proved minor sensitivities of pyrolysis process to the fuels physiochemical properties for the persistent conversion and destruction of HFS. Earlier research on larger particle sizes of faecal sludge and excessive moisture contents confirmed their disruptive role during gasification/combustion reactions, delaying ignition and subsequent conversion processes. In such applications, the particle size can be considered as a non-controllable parameter unless a primary stage of particle size reduction is provisioned. Meanwhile, utilisation of dewatering and drying stages prior to these processes are found necessary to reduce the moisture content to certain levels enabling consistent conversion of fuel in very short reaction times. On top of these, particle size and shape of the solids have also been found to play an adverse role for drying and moisture reduction. All of these necessitate the precise automation and advanced optimisation of systems employing gasification and combustion to fully convert the sludge with alternative physiochemical properties. Investigated in this research project, the partially dried faecal sludge

from the dryer had different particle size/shapes and moisture contents. It was observed that the elevation of temperature to 450°C and above, alongside longer solid residence times in comparison to combustion/gasification enabled the complete conversion of raw solids to by-products. However, the extent of conversion remained different, and the product yields and specifications altered. Thus, it can be concluded that pyrolysis performed less sensitive to the fuel's physical properties than combustion and gasification. The leading research undertaken in this thesis displayed important information on the properties of pyrolytic products from non-sewered HFS sanitary wastes. The evolutions of pyrolytic products were discussed with respect to the variation of process parameters enabling remarkable insights into the negative-emission processing of the HFS.

Overall, this thesis underpinned a profound benchmark for the implementation of emerging thermal processes within the context of next generation closed-loop sanitary systems.

6.6 Conclusions

This project aimed to develop an innovative solid waste management process in the context of a wastewater treatment system installed on trains. The result was the pyrolysis system that allowed the complete and persistent thermal conversion of human faecal sludge in a very short processing timeframe. The topics comprehensively investigated in this thesis have been evident of this.

This Chapter summarised the work packages undertaken to achieve the aims and objectives of this project. Limitations of the research as well as recommendations for future work were made.

This research possesses originality in:

- The design and development of a ground-breaking solid waste management system for sanitary applications;
- Characterisation and identification of wastes generated in rolling stock;

- Chemical conversion of human faecal sludge within drying and pyrolysis conditions in a novel system;
- Application of a novel thermal treatment system suitable for managing human faecal sludge produced in trains. Such a system has not previously been investigated.

Future research in the utilisation of these technologies could result in further improvements of such highly advanced technologies, addressing sewage waste management in different communities and a range of industry sectors. It is envisaged that this technology could also have significant impact in remote applications where sewage connections are not accessible. This includes the transport, thus the system could be utilised in aviation and shipping.

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Appendix

Data Appendices

- A- Chapter 3, MATLAB code for DAEM development
- B- Chapter 3, TGA graphs for FS2 and TT
- C- Chapter 3, Kinetic parameters of HFS and train tissue samples obtained from DAEM
- D- Chapter 5, theoretical design data for twin auger reactor
- E- Chapter 5, temperature profile within the pyrolysis unit
- F- Chapter 5, List of identified hydrocarbons in biooils from test set A & B plus chromatograms
- G- Chapter 5, supplementary photo of the twin auger reactor

Publications Appendices

Journal Publications:

- H- (2021) Review article: Managing Non-Sewered Human Waste Using Thermochemical Waste Treatment Technologies: A Review. *Energies*. (Modified from Chapter 2) - <https://doi.org/10.3390/en14227689>

Conference presentations:

- I- The overall research carried out during this PhD program was presented in the 1st FERIA conference held in Nottingham, UK, THE EUROPEAN CONFERENCE ON FUEL AND ENERGY RESEARCH AND ITS APPLICATIONS.

Appendix A - Chapter 3, MATLAB code for DAEM development

```

%% eliminate Nans
LnBetaT1squared(isnan(T1Reciprocal)) = [];
Weight1(isnan(T1Reciprocal)) = [];
T1Reciprocal(isnan(T1Reciprocal)) = [];
LnBetaT2squared(isnan(T2Reciprocal)) = [];
Weight2(isnan(T2Reciprocal)) = [];
T2Reciprocal(isnan(T2Reciprocal)) = [];
LnBetaT3squared(isnan(T3Reciprocal)) = [];
Weight3(isnan(T3Reciprocal)) = [];
T3Reciprocal(isnan(T3Reciprocal)) = [];
LnBetaT4squared(isnan(T4Reciprocal)) = [];
Weight4(isnan(T4Reciprocal)) = [];
T4Reciprocal(isnan(T4Reciprocal)) = [];
%%
weightstar_1 = Weight1(1) - Weight1(end);
weightstar_2 = Weight2(1) - Weight2(end);
weightstar_3 = Weight3(1) - Weight3(end);
weightstar_4 = Weight4(1) - Weight4(end);
%% defining v/v*
volatileRatioValue1 = (Weight1(1) - Weight1(2:end))/weightstar_1;
volatileRatioValue2 = (Weight2(1) - Weight2(2:end))/weightstar_2;
volatileRatioValue3 = (Weight3(1) - Weight3(2:end))/weightstar_3;
volatileRatioValue4 = (Weight4(1) - Weight4(2:end))/weightstar_4;
%%
volatileRatioStep = 0.05;
maxVolatilieRatio = 0.9;
minVolatilieRatio = 0.1;
V1 = volatileRatioValue1;
V2 = volatileRatioValue2;
V3 = volatileRatioValue3;
V4 = volatileRatioValue4;
%%
linearVolatileRatios = [maxVolatilieRatio:-volatileRatioStep:minVolatilieRatio];
%% Variables for Arrhenius
[~, V1Chosen] = min(abs(repmat(V1, 1, length(linearVolatileRatios)) -
linearVolatileRatios));
[~, V2Chosen] = min(abs(repmat(V2, 1, length(linearVolatileRatios)) -
linearVolatileRatios));
[~, V3Chosen] = min(abs(repmat(V3, 1, length(linearVolatileRatios)) -
linearVolatileRatios));
[~, V4Chosen] = min(abs(repmat(V4, 1, length(linearVolatileRatios)) -
linearVolatileRatios));
X1 = T1Reciprocal(1 : end);
X2 = T2Reciprocal(1 : end);
X3 = T3Reciprocal(1 : end);

```

```

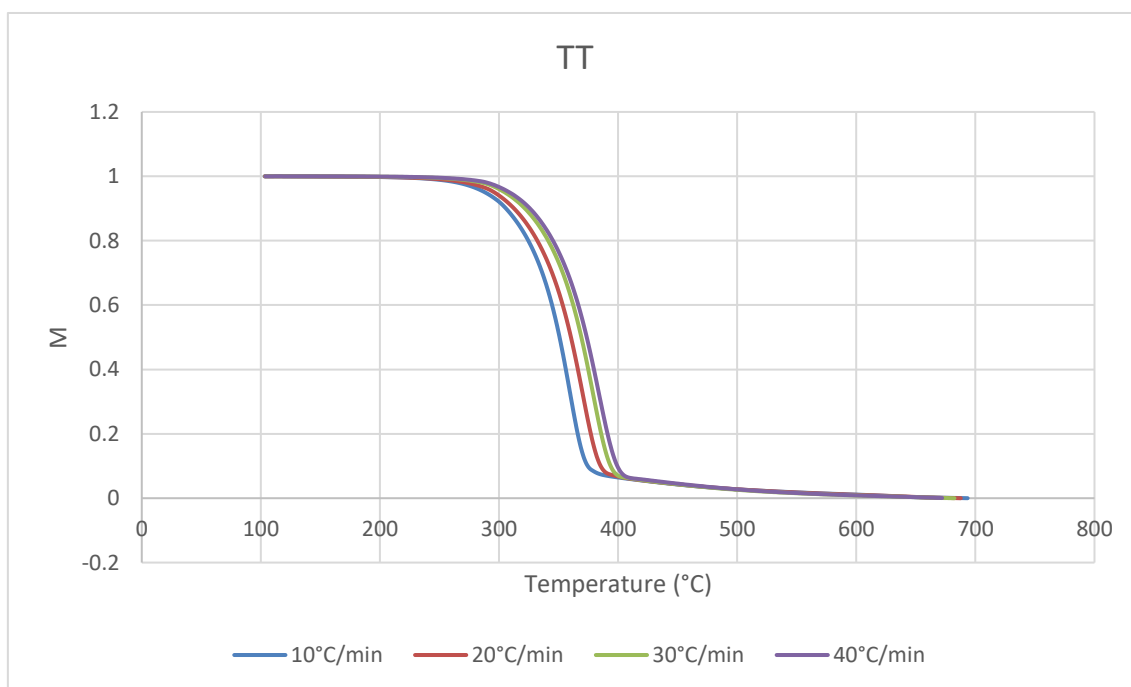
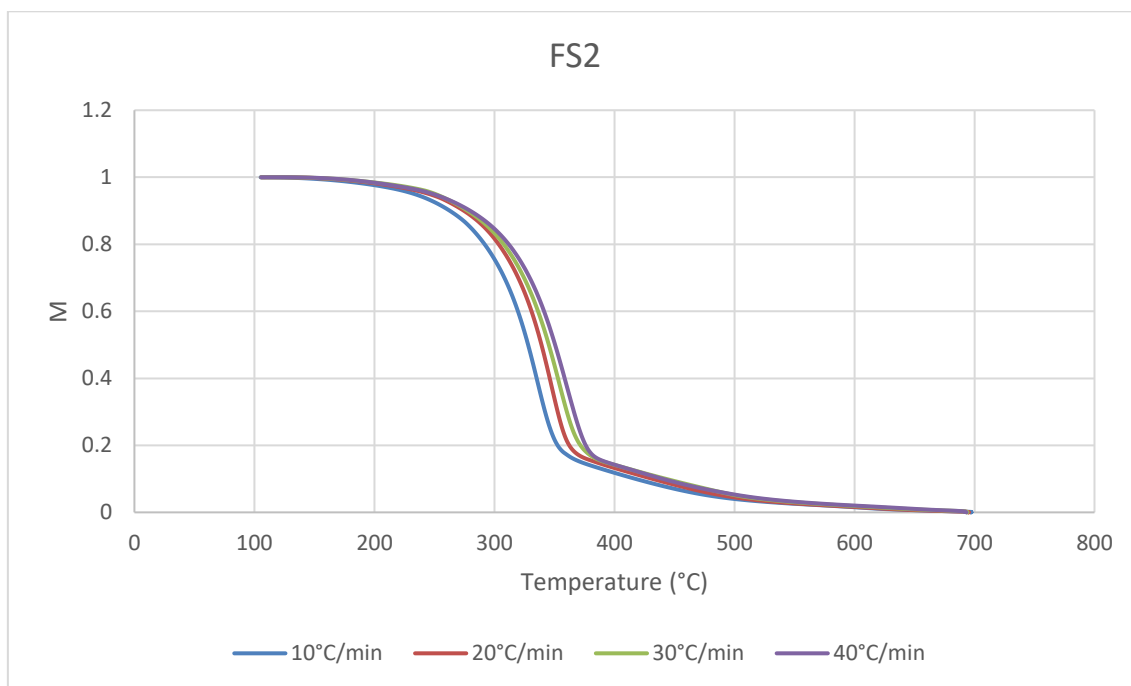
X4 = T4Reciprocal(1 : end);
Y1 = LnBetaT1squared(1 : end);
Y2 = LnBetaT2squared(1 : end);
Y3 = LnBetaT3squared(1 : end);
Y4 = LnBetaT4squared(1 : end);
%% Arrhenius plot
plot(X1 , Y1);
hold on
plot(X2, Y2);
plot(X3 , Y3);
plot(X4 , Y4);
plot(X1(V1Chosen) , Y1(V1Chosen) , '*')
plot(X2(V2Chosen) , Y2(V2Chosen) , 'O')
plot(X3(V3Chosen) , Y3(V3Chosen) , '+')
plot(X4(V4Chosen) , Y4(V4Chosen) , 'x')
ylabel 'Ln Beta/T^2'
xlabel '(1/T)*1000'
title 'Arrhenius plot (FS1)'
%% Fitted lines between point of different conversion rates
fitX = [X1(V1Chosen) , X2(V2Chosen) ,X3(V3Chosen) , X4(V4Chosen)];
fitY = [Y1(V1Chosen) , Y2(V2Chosen) , Y3(V3Chosen) , Y4(V4Chosen)];
slopes = zeros(length(V1Chosen) , 1);
intercepts = slopes ;
rSquared = slopes;
for i = 1:length(V1Chosen)
[fitLine , gof] = fit(fitX(:,i) , fitY(:, i) , 'poly1');
rSquared(i) = gof.rsquare;
slopes (i) = fitLine.p1;
intercepts(i) = fitLine.p2;
hold on
plot([fitX(1 , i) , fitX(end , i)] , [fitLine.p1*fitX(1 , i) , fitLine.p1*fitX(end ,
i)]+fitLine.p2)
end
% calculation of E via slopes from the equation containing the arrhenius
% legends
R = 8.314;
activationEnergies = -slopes * R;
correlationFactors = (exp(intercepts - 0.6075)).*activationEnergies / R;
figure
subplot(2 , 1 ,1 )
yyaxis left
plot(linearVolatileRatios , activationEnergies , '-.')
ylabel 'E(Kj mol^-1)'
xlabel '\alpha'
yyaxis right
plot(linearVolatileRatios, rSquared , 'bla-.');
ylabel R^2

```

```

legend 'Activation Energy' ' R^2'
title 'Activation energy (FS1)'
subplot(2 , 1 , 2)
plot(correlationFactors);
title 'Correlation factor'
figure
plot (activationEnergies , correlationFactors)
set (gca , 'YScale' , 'log')
ylabel '\alpha'
xlabel 'E (Kj mol^-1)'
%%
figure
plot(1000./(X1(V1Chosen)) , linearVolatileRatios)
hold on
plot(1000./(X2(V2Chosen)) , linearVolatileRatios)
plot(1000./(X3(V3Chosen)) , linearVolatileRatios)
plot(1000./(X4(V4Chosen)) , linearVolatileRatios)
ylabel 'volatile ratios '
xlabel 'temperature (K)'
legend Experiment1 Experimnet2 Experiment3 Experiment4
%%
figure
plot (activationEnergies,linearVolatileRatios)
ylabel 'volatile ratios'
xlabel 'Activation Energies'

```

Appendix B - Chapter 3, TGA graphs for FS2 and TT

Appendix C - Chapter 3, kinetic parameters of HFS and train tissue samples obtained from DAEM

conversion	FS1			FS2			TT		
	K ₀	E (kJ/mol)	R ²	K ₀	E (kJ/mol)	R ²	K ₀	E (kJ/mol)	R ²
0.1	0.0E+00	159.56	0.635	6.0E+11	202.51	0.907	3.2E+12	198.40	0.997
0.15	8.9E+12	203.02	0.912	2.2E+14	220.02	0.977	7.0E+11	188.77	0.997
0.2	2.6E+12	193.12	0.973	5.8E+12	194.47	0.989	9.6E+11	189.43	0.998
0.25	6.0E+12	195.72	0.974	1.9E+12	186.94	0.991	7.4E+11	187.21	0.995
0.3	1.1E+13	197.14	0.976	1.5E+12	184.36	0.991	6.5E+12	197.70	0.996
0.35	3.0E+12	189.33	0.982	2.6E+12	186.12	0.995	3.0E+12	192.93	0.993
0.4	6.7E+12	192.26	0.969	8.1E+12	190.68	0.996	5.5E+12	195.27	0.994
0.45	1.3E+13	194.61	0.981	7.7E+12	189.34	0.999	5.7E+12	194.57	0.995
0.5	3.6E+13	198.48	0.969	1.4E+13	190.91	1.000	4.2E+12	192.09	0.990
0.55	1.9E+14	205.41	0.972	1.6E+14	201.50	0.998	1.0E+13	195.64	0.987

0.6	3.2E+14	206.47	0.965	5.2E+13	194.74	1.000	3.6E+13	200.94	0.991
0.65	4.3E+14	205.97	0.937	6.0E+13	193.66	0.994	4.9E+13	201.16	0.989
0.7	3.3E+14	202.60	0.917	1.2E+14	194.74	0.994	7.9E+13	201.91	0.982
0.75	4.4E+14	201.46	0.941	1.5E+14	193.63	0.992	3.6E+13	196.32	0.980
0.8	4.6E+14	198.63	0.894	2.8E+14	193.27	0.982	5.8E+13	196.41	0.979
0.85	1.3E+14	188.67	0.880	2.6E+15	199.22	0.972	1.8E+13	187.92	0.967
0.9	2.0E+14	185.39	0.893	9.8E+15	198.64	0.948	1.3E+13	183.01	0.968

Appendix D - Chapter 5, Theoretical design data for twin auger reactor

The fundamental mass transfer and heat transfer calculations as well as some of the basic concepts in the design and fabrication of screw conveying reactors are mentioned below:

The calculations are completed using the available literature data on sewage waste and faecal sludge materials:

Analysis	Parameters	Unit	Value	Equation	Reference
Inlet Biomass	Mass flow rate	kg/hr	4	$\dot{M}_b$	--
	Density	kg/m ³	~1600	ρ_b	[228]
	Volumetric feed	cm ³ /min	41.66	$\dot{Q}_b : \dot{M}_b / P_b$	--
	Specific heat capacity	kJ/kg*K	~4	C_p	[193]

Product solid char	Yield (dry)	Wt.%	0.29	CH_{yield}	[170]
	Density	kg/m ³	420	ρ_{CH}	[229]
	Mass flow rate	Kg/hr	1.16	$\dot{M}_{CH} : CH_{yield} * \dot{M}_b$	--
	Volumetric flow rate	cm ³ /min	46.03	$\dot{Q}_{CH} : \dot{M}_{CH} / \rho_{CH}$	--
	Yield (dry)	Vol.%	1.10	$CH_{yield,vol\%} : \dot{Q}_{CH} / \dot{Q}_b$	--

Pyrolytic Bio-oil, Vapour and aerosol	Mass flow rate	kg/hr	2.84	$\dot{M}_V : \dot{M}_b - \dot{M}_{CH}$	--
	Molecular weight	kg/kmol	88.68	MW_V	[176]
	Universal gas constant	J/kmol*K	8314	R	[230]
	Product stream pressure	pa	101325	P_V	--
	Product stream temperature	K	773.15	T_V	--
	Product gas constant	j/kg*K	93.75	$R_V : R / MW_V$	--
	Mass density, ideal gas law	Kg/m ³	1.39	$P_M : P_V / R_V * T_V$	--

	Volumetric flow rate	L/min	33.86	$\dot{Q}_V : \dot{M}_V / \dot{M}_p$	--
--	----------------------	-------	-------	-------------------------------------	----

	Volumetric % fill of biomass	--	0.5	δ_b	--
	Volumetric % of excavated area	--	0.5	δ_{ea}	--
	Volume percent fill of char	--	0.55	$\delta_{ch} : CH_{yield, vol\%} * \delta_b$	--
	Volume percent fill of vapours	--	0.45	$\delta_p : 1 - \delta_{ch}$	--

Pyrolysis reactor cross sectional area	Screw pitch	cm	7.2	P_s	--
	Rotation speed	RPM	1	S_s	--
	Screw rotation frequency	1/s	0.016	S_{rf}	--
	Biomass linear velocity	cm/s	0.12	$V_b : S_{rf} * P_s$	--
	Cross sectional area for biomass	cm ²	5.78	$A_{csb} : \dot{M}_b / (\rho_b * V_b)$	--

	Total required cross section based on reactor percent fill of 0.5	cm ²	11.57	$A_{Tcsb} : A_{csb} / \delta_b$	--
--	---	-----------------	-------	---------------------------------	----

Pyrolysis reactor dimensions	Reactor width (Rectangular)	cm	14.4	w	--
	Reactor height (Rectangular)	cm	8.2	h	--
	Shaft diameter	cm	3	S _o	--
	Auger diameter	cm	7.2	D _o	--
	Pitch	cm	7.2	P _s	--

Vapour residence time	Cross sectional area for solids (biomass and char)	cm ²	117	$A_{css} : (w * h) - (1.5 (\pi/4) * d_s^2)$	--
	Cross sectional area for vapours (reactor percent fill of 0.5)	cm ²	108.2	$A_{csv} : A_{css} * \zeta_v$	--
	Vapour velocity	cm/s	3.93	$V_v : \dot{M}_v / P_M * A_{csv}$	--

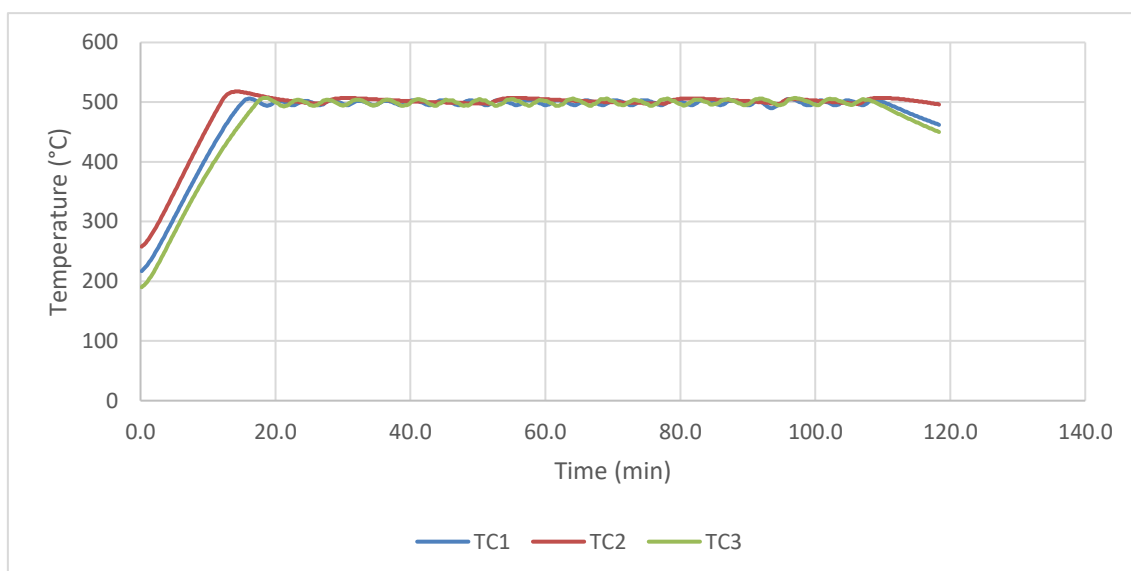
Vapour residence time	Vapour velocity: 3.93 cm/s	Intermediate pyrolysis (mm)	Distance from the biomass centre inlet (mm)
		7.5	295
		10	395
		13.5	530
		17	670
		20	790

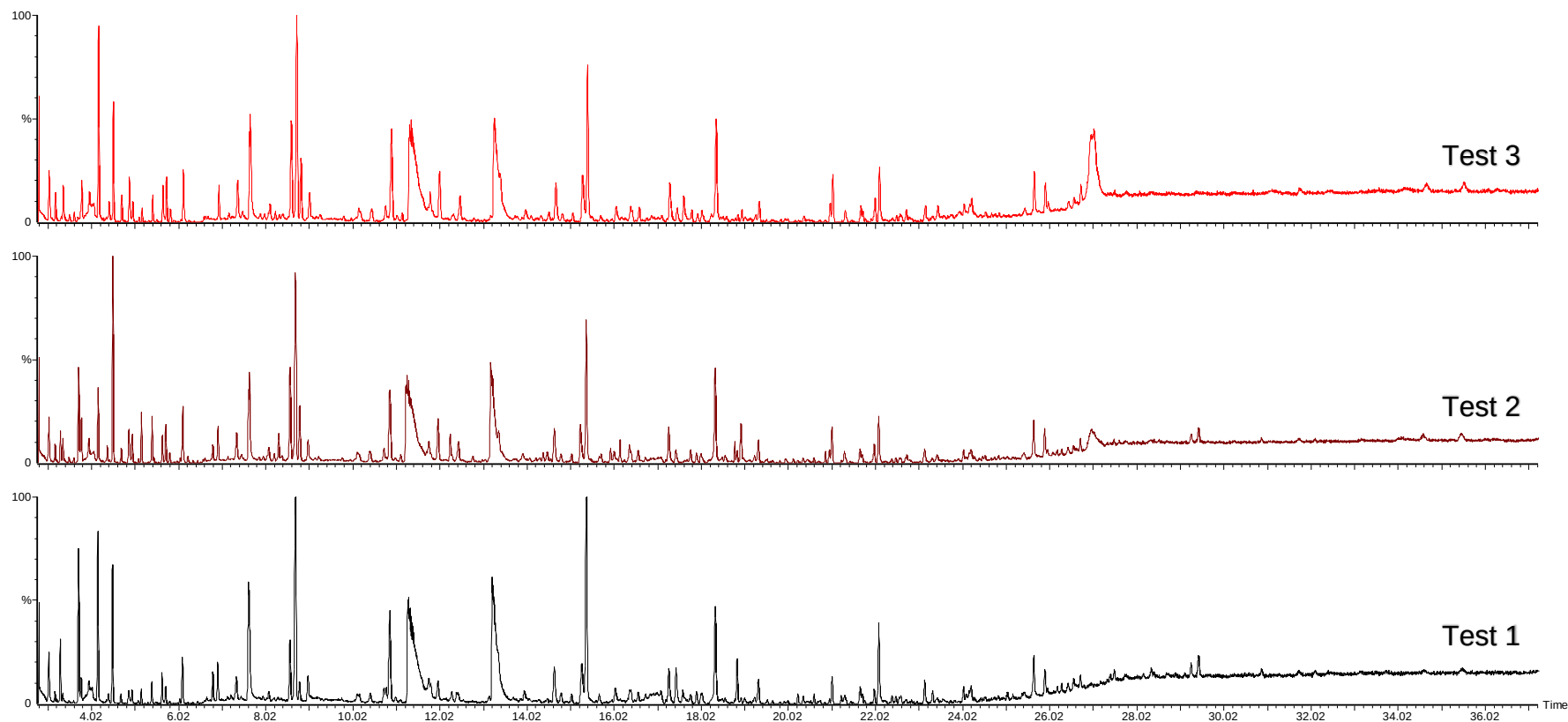
Heat transfer	Initial temperature	(K)	25 + 273.15	T_1	--
	Final temperature	(K)	450 + 273.15	T_2	--
	Heat for Pyrolysis	MJ/kg	3	Q_b	--
	Required sensible heat 25-450	MJ/kg	1.77	$Q_{sens} : C_p * (T_2 - T_1)$	--

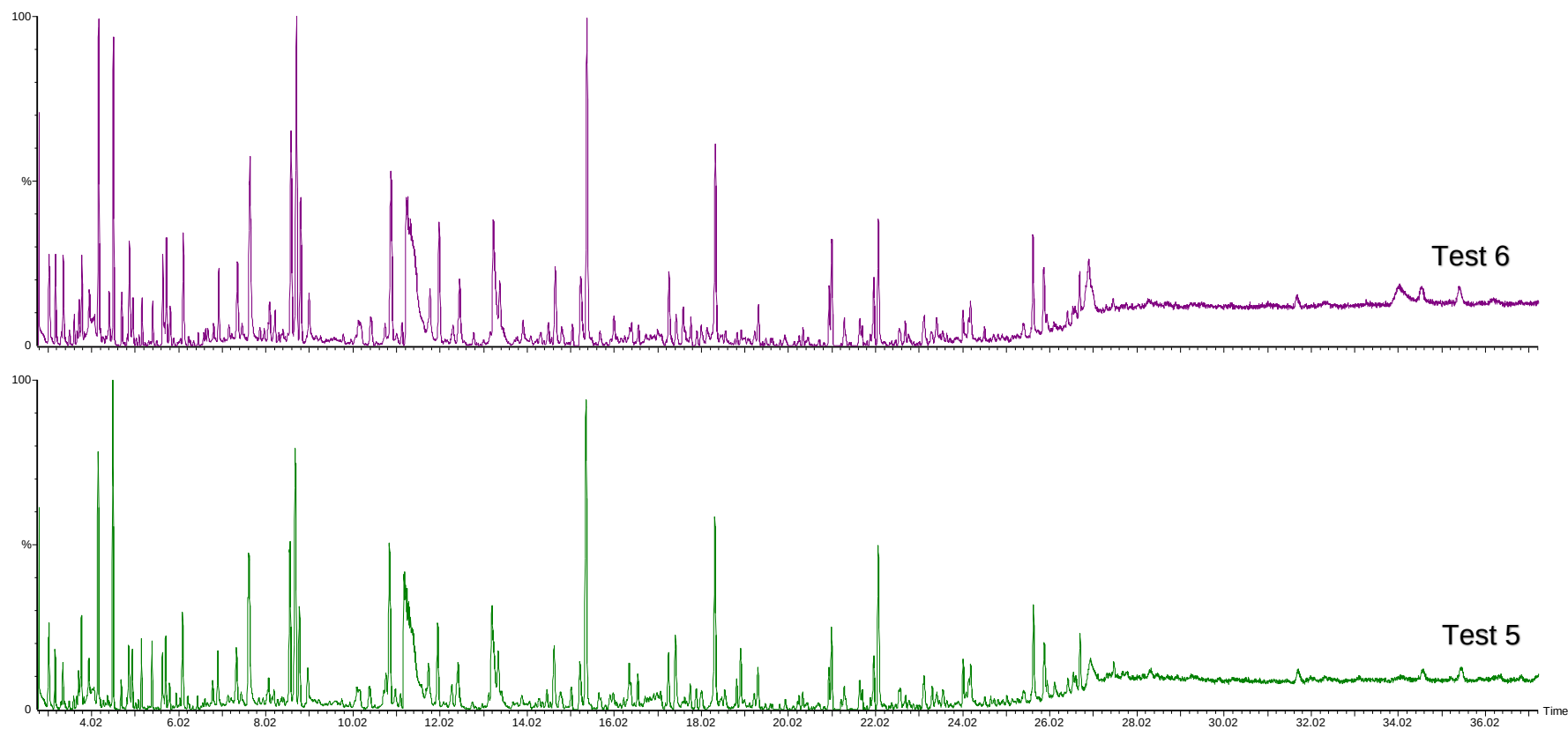
	Heat transfer rate required for pyrolysis	KW	~3.5	$Q_{Eb} : Q_b * \dot{M}_b$	--
	Reaction heat required for pyrolysis	MJ/kg	1.22	$Q_{Rb} : Q_{Eb} - Q_{sens}$	--

Appendix E - Chapter 5, Temperature profile within pyrolysis reactor

An example of heat profile within the pyrolysis reactor recorded by the thermocouples showcased in Figure 5-4, until a steady state throughout the tube.



Appendix F - Chapter 5, List of identified hydrocarbons from test set A & B plus chromatograms



A	Test 1			Test 2			Test 3		
No	RT/ min	Compound name	Area/ %	RT/ min	Compound name	Area/ %	RT/ min	Compound name	Area/ %
1	3.05	2,3-Butanedione	0.71	3.05	2,3-Butanedione	0.79	3.05	2,3-Butanedione	0.80
2	3.31	Methyl methacrylate	0.68	3.73	Toluene	1.22	3.97	2,3-Pentanedione	0.78
3	3.72	Toluene	1.85	3.96	2,3-Pentanedione	0.68	4.19	Cyclohexane	2.92
4	3.96	2,3-Pentanedione	0.59	4.18	Cyclohexane	1.13	4.52	Oxazole, 4,5-dihydro- 2,4,4-trimethyl-	1.43
5	4.16	Cyclohexane	2.44	4.51	Oxazole, 4,5-dihydro- 2,4,4-trimethyl-	3.49	4.90	3-Penten-2-one, (E)-	0.60
6	4.50	Oxazole, 4,5-dihydro- 2,4,4-trimethyl-	1.86	5.17	2-Propanone, (1- methylethylidene) hydrazone	0.72	6.13	4- Pyridinecarboxaldehy de	0.76

7	6.11	1,3-Diazine	0.67	6.12	4-Pyridinecarboxaldehyde	1.00	7.38	Acetoin	0.71
8	6.92	Pyrazine, methyl-	0.55	7.35	Acetoin	0.66	7.66	Ethyl aminomethylformimidate	2.73
9	7.63	Ethyl aminomethylformimidate	3.01	7.65	N-Nitrosodimethylamine	2.46	8.61	2-Cyclopenten-1-one	1.89
10	8.58	2-Cyclopenten-1-one	1.07	8.58	2-Cyclopenten-1-one	2.21	8.73	3-Octanol	4.26
11	8.71	3-Octanol	4.17	8.70	3-Octanol	4.60	8.83	2-Cyclopenten-1-one, 2-methyl-	1.06
12	8.99	1-Hydroxy-2-butanone	0.75	8.80	2-Cyclopenten-1-one, 2-methyl-	1.15	9.03	1-Hydroxy-2-butanone	0.63
13	10.88	Furfural	2.04	10.87	Furfural	2.04	10.91	Furfural	1.89

14	11.3 0	Acetic acid	10.37	11.2 6	Acetic acid	3.53	11.3 2	Propanedioic acid	2.18
15	11.7 6	Ethanone, 1-(2-furanyl)-	0.70	11.3 1	Oxalacetic acid	6.92	11.3 6	Ethyl hydrogen malonate	0.76
16	13.2 2	Propanoic acid	7.88	11.7 6	Ethanone, 1-(2-furanyl)-	0.87	11.3 9	(3-Carboxypropyl) trimethylammonium cation	6.80
17	14.6 5	Butanoic acid, 4-hydroxy-	0.89	11.9 8	2-Cyclopenten-1-one, 3-methyl-	1.06	11.8 0	Ethanone, 1-(2-furanyl)-	0.92
18	15.2 8	Butanoic acid	1.15	13.1 9	Propanoic acid	6.05	12.0 2	2-Cyclopenten-1-one, 3-methyl-	0.99
19	15.3 9	2-Furanmethanol	4.60	13.3 7	2-Furancarboxaldehyde, 5-methyl-	1.68	12.4 8	2-Cyclopenten-1-one, 2,3-dimethyl-	0.61
20	17.2 7	Acetamide	0.78	14.6 5	Butanoic acid, 4-hydroxy-	0.93	13.2 7	Propanoic acid	6.91

21	17.4 4	1,2-Cyclopentanedione	0.78	15.2 4	Butanoic acid	1.01	14.6 9	Butyrolactone	0.91
22	18.3 4	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.42	15.3 8	2-Furanmethanol	3.13	15.3 0	Butanoic acid	1.04
23	18.8 4	Phenol, 2-methoxy-	0.71	17.2 8	Ethanimidic acid, ethyl ester	0.89	15.4 1	2-Furanmethanol	2.74
24	22.1 0	Butanal, 3-methyl-	1.58	18.3 4	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.69	17.2 9	Acetamide	0.99
25	25.6 6	1,4:3,6-Dianhydro- α -d-glucopyranose	0.88	18.9 3	2-Octanol, acetate	0.89	18.3 7	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.44
26	27.5 0	α -d-Lyxofuranoside, O-nonyl-	0.55	21.0 2	Phenol	0.78	21.0 4	Phenol	0.91
27	27.7 5	Pyrrolizin-1,7-dione-6-carboxylic acid, methyl(ester)	0.54	22.0 9	Cyclopentanol	1.12	22.1 2	Cyclopentanol	1.08

28	28.3 5	(+)-s-2- Phenethanamine, 1- methyl-N-vanillyl-	0.54	25.6 5	1,4:3,6-Dianhydro-à- d-glucopyranose	0.97	25.6 7	1,4:3,6-Dianhydro-à- d-glucopyranose	0.91
29	29.2 6	Aflatoxin G2	0.64	25.9 1	3-Pyridinol	0.65	25.9 2	3-Pyridinol	0.58
30	29.4 3	Aflatoxin B1	0.65	26.9 8	9-Octadecenamide, (Z)-	2.42	27.0 4	9-Octadecenamide, (Z)-	7.25

B	Test 5			Test 6		
No.	RT/min	Compound name	Area/%	RT/min	Compound name	Area/%
1	3.046	2,3-Butanedione	0.853	3.053	2-Pentanone	0.942
2	3.79	2,4-Dimethyl-2-oxazoline-4-methanol	0.7744	3.376	Acetonitrile	0.8003
3	4.175	Cyclohexane	2.415	4.19	Hexanoic acid, 5-hydroxy-3-methyl-, ð-lactone	2.833

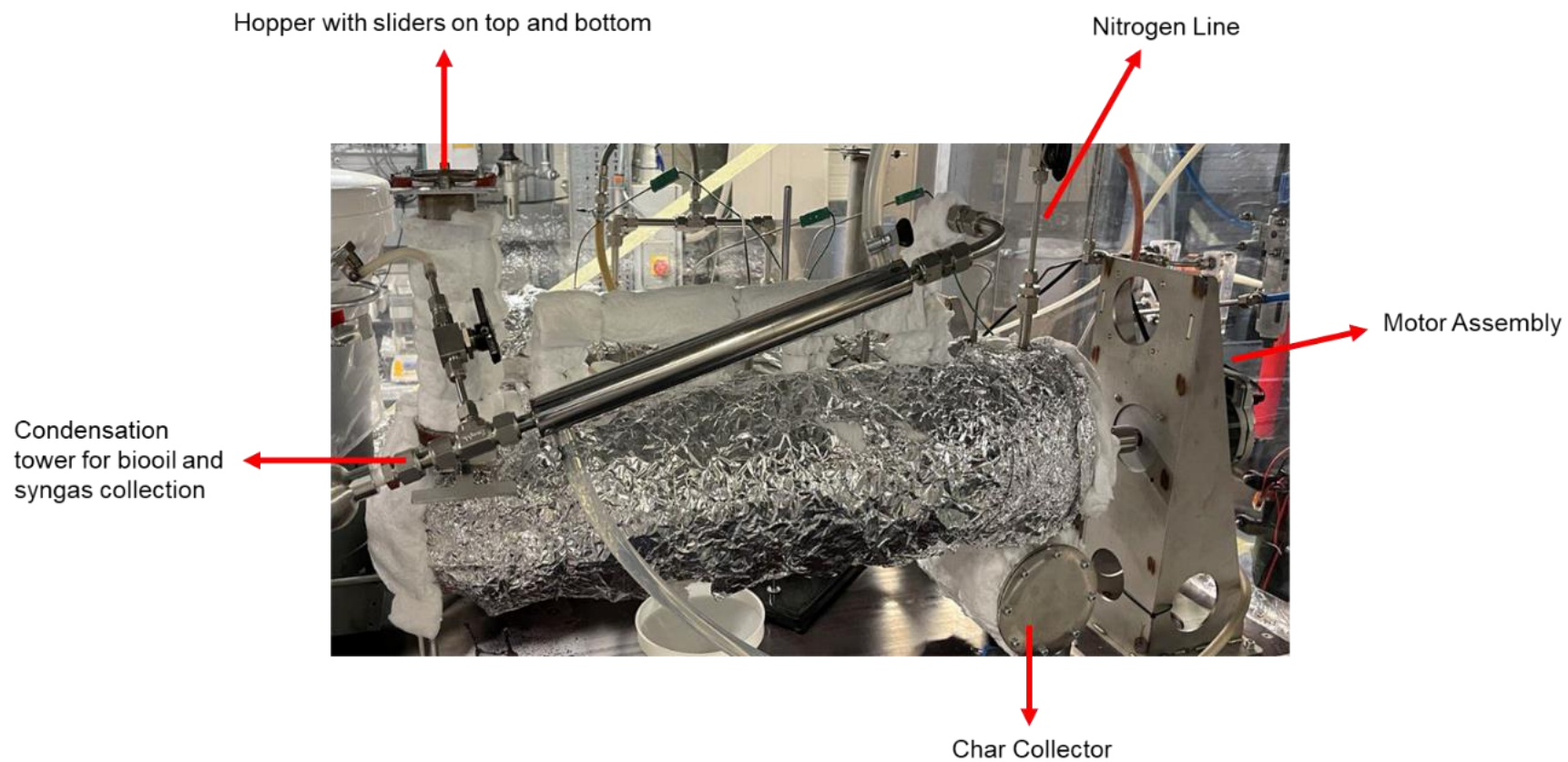
4	4.513	Oxazole, 4,5-dihydro- 2,4,4-trimethyl-	2.564	4.524	Oxazole, 4,5-dihydro- 2,4,4-trimethyl-	2.108
5	6.113	4- Pyridinecarboxaldehyde	0.8944	4.895	3-Penten-2-one, (E)-	0.8744
6	7.635	Ethyl aminomethylformimidate	2.211	6.127	4-Pyridinecarboxaldehyde	1.001
7	8.578	Furan, 2-methyl-	1.907	7.371	3-Hydroxy- butansaeureanilid	0.8358
8	8.692	3-Octanol	3.209	7.657	Ethyl aminomethylformimidate	2.56
9	8.798	2-Cyclopenten-1-one, 2- methyl-	1.071	8.604	Furan, 2-methyl-	2.321
10	10.86	Furfural	2.432	8.732	3-Octanol	3.65
11	11.21	Propanedioic acid	4.147	8.824	2-Cyclopenten-1-one, 2- methyl-	1.51

12	11.31	Acetamide	4.195	9.014	1-Hydroxy-2-butanone	0.7721
13	11.97	2-Cyclopenten-1-one, 3-methyl-	1.063	10.89	Furfural	2.512
14	12.43	2-Cyclopenten-1-one, 2,3-dimethyl-	0.8817	11.28	Acetic acid	3.681
15	13.21	Propanoic acid	2.42	11.34	Acetic acid, hydrazino-, ethyl ester	4.983
16	13.36	2-Furancarboxaldehyde, 5-methyl-	0.9281	12	2-Cyclopenten-1-one, 3-methyl-	1.45
17	14.64	Butanoic acid, 4-hydroxy-	0.884	12.47	2-Cyclopenten-1-one, 2,3-dimethyl-	1.003
18	15.23	Propanedioic acid, propyl-	0.7422	13.24	Propanoic acid	2.624
19	15.37	2-Furanmethanol	3.976	13.39	2-Furancarboxaldehyde, 5-methyl-	1.025

20	16.36	Cyclohexanespiro-5'-(2',4',4'-trimethyl-2'-oxazoline)	0.7694	14.67	Butanoic acid, 4-hydroxy-	0.998
21	17.42	1,2-Cyclopentanedione	0.9384	15.25	Butanoic acid	1.098
22	18.33	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.674	15.39	2-Furanmethanol	3.88
23	21.01	Phenol	0.8363	17.28	Ethanimidic acid, ethyl ester	0.856
24	21.98	Phenol, 3-methyl-	0.6815	18.34	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	2.52
25	22.08	3,6-Octadecadiynoic acid, methyl ester	2.048	21.02	Phenol	1.162
26	25.64	1,4:3,6-Dianhydro- α -D-glucopyranose	1.3	21.98	Phenol, 3-methyl-	0.7586
27	25.89	3-Pyridinol	0.8044	22.09	dl-Leucine, N-[(phenylmethoxy)carbonyl]-	1.438

28	26.95	9-Octadecenamide, (Z)-	1.554	25.63	1,4:3,6-Dianhydro- α -D-glucopyranose	1.169
29	27.49	α -D-Lyxofuranoside, O-nonyl-	0.7955	25.88	3-Pyridinol	0.8188
30	28.35	1-(4-methylthiophenyl)-2-propanone	0.7531	26.91	9-Octadecenamide, (Z)-	2.507

Appendix G - Chapter 5, Supplementary photo of the twin auger pyrolysis reactor



Appendix H - Review article 2021 - Managing Non-Sewered Human Waste Using Thermochemical Waste Treatment Technologies: A Review. Energies.

(Modified from Chapter 2)

Review

Managing Non-Sewered Human Waste Using Thermochemical Waste Treatment Technologies: A Review

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Abstract: The utilisation of micro-scale thermal treatment technologies for non-sewered applications has been emerging as a prominent route for the safe treatment and disposal of high water content hazardous feedstock. This study provides a comprehensive review of the technological concepts practiced up to date in commercial/pilot and small scales for various types of solid fuels. The respective challenges are critically described and discussed to aid in the selection of promising technology for on-site sanitary applications. Furthermore, the challenges observed with the nominated (pyrolysis) technology are discussed in detail and addressed. This study suggests rapid energy recovery from by-products primarily made up of the highest yield of syngas with a desirable calorific value. The optimum operating ranges are discussed to ensure a reliable thermal conversion of sludge materials considering the application constraints and technology drawbacks. However, further studies are needed to investigate the uncertainties regarding emissions, energy consumption and overall associated costs.

Keywords: sewage sludge; faecal; combustion; gasification; pyrolysis; thermochemical conversion; syngas; bio-oil



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1. Introduction

The human population produces a significant amount of sanitary waste every year, up to 55.1 kg/person/year, which equates to an overall figure of around 385 million tonnes per year for a global population of 7 billion [1]. Human excreta is a hazardous waste that needs to be managed safely. Faecal sludge (FS) is a generic term referring to the mixture of undigested or partially digested slurry/solids resulting from the storage or treatment of black water or excreta with or without grey water [2]. In general, faecal sludge management (FSM) includes storage, collection, transport and treatment in wastewater treatment plants (WWTPs) and the safe end use or disposal of FS [2]. However, FSM also relates to non-sewered sanitation systems such as pit latrines and septic tanks [3]. Several organisations such as the international sanitation community, Water and Sanitation for the Urban Poor (WSUP) and The Bill and Melinda Gates Foundation have supported initiatives with a focus on FSM challenges in low-income countries [2–4]. In contrast to FSM, sewerage sanitation is only concerned with wastewater/sewage treatment [5].

A typical wastewater treatment plant (WWTP) receives polluted wastewater from multiple sources, including municipal and commercial sources, in the form of water, human excreta, personal care products, etc. The two products of WWTPs are effluent and sludge, which need to be of adequate quality for disposal according to the Urban Wastewater Treatment European Directive (UWED) in the EU [6]. Common methods of the disposal of treated sludge are landfilling, land application as a fertiliser and combustion. According to Eurostat [7], two of the commonly used methods in the EU have remained as agricultural use and combustion. However, land disposal and combustion are subject to increasingly

strict regulations due to pathogen risks, greenhouse gas emissions from microorganism activities due to inefficient organic removal and a large amount of flue gas emissions, respectively [8]. Details about the European parliament and council directives can be found in [6,9]. Currently, the recycling of sewage sludge through agricultural lands is legal in the UK and accounts for almost 80% [10] of the overall volume. Land spreading is banned in some EU countries, such as the Netherlands, where combustion is favourable due to concerns over the safety of its use in farmlands [11]. These risks include the presence of pathogens such as *Escherichia coli* and salmonella, persistent organic pollutants, heavy metals and microplastics [12]. Hence, future resilience through the implementation of robust and sustainable treatment processes is of high importance to tackle associated challenges with such waste materials.

Despite several variations of WWTPs, most of them currently follow the same route for the treatment of wastewater/sewage sludge: (1) preliminary treatment, (2) primary treatment and (3) secondary treatment. An inevitable by-product of raw sewage treatment is the sludge generated from the primary and secondary steps. After removing large objects via straining with bar screens (preliminary step), the suspended solids in the water column settle at the bottom of the tank due to gravitational differences in the primary step. The sludge generated is a semi solid/slurry that includes 50–70% suspended solids, which is pumped toward the sludge treatment process. Further on, using biological processes, non-colloidal solids are removed and organic constituents are stabilised, namely ‘secondary sludge’. The generated sludge is further treated following the sequence of thickening and dewatering (centrifuge, plate press, belt press, etc.), conditioning (thermal, chemical) and final treatment (composting, combustion, thermal treatment, wet oxidation, etc.), storage (liquid sludge, dry sludge, ash) and transportation for landfilling, agriculture or other uses, as depicted in Figure 1 [9]. All these methods aim for the stabilisation of the biodegradable fraction of the organic matter for reducing the risk of putrefaction, diminishing the concentration of pathogens, reducing weight and volume and odour elimination [13].

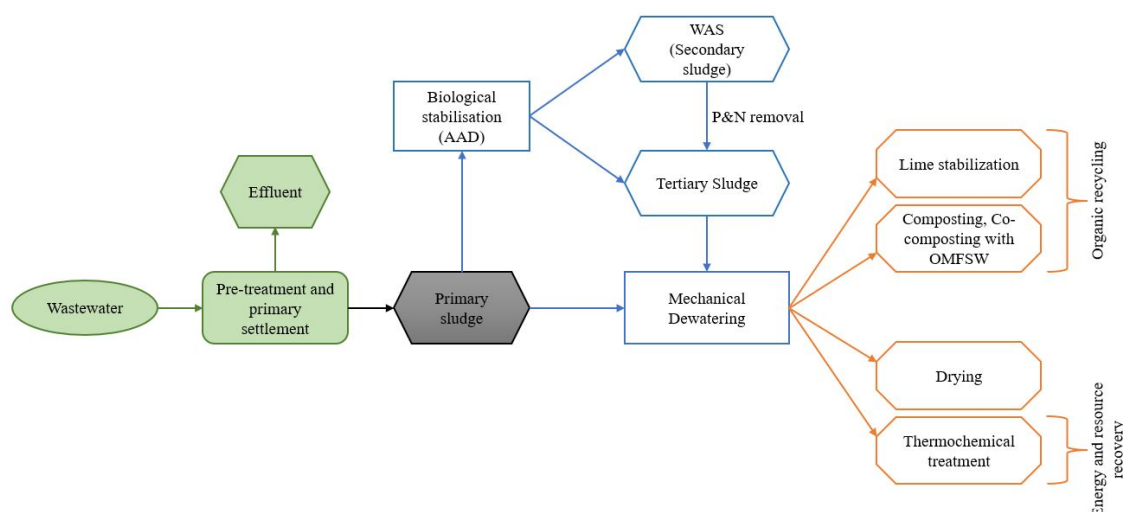


Figure 1. Sewage sludge treatment processes (AAD—Anaerobic digestion, WAS—Waste-activated sludge, OMFSW—Organic fraction of municipal solid waste) [9,14,15].

The characteristics of outputs from wastewater treatment processes depend on the production/treatment route pursued and the origins of the sewage. An example of a stabilisation technique for sewage sludge is anaerobic digestion in the secondary treatment step from which the product can be utilised as fertiliser. In addition, this process can recover energy by harnessing the biogas released from the digester [16].

One objective of this critical review is to discuss the solid waste management/stabilisation technologies and their operational challenges. The state of the art of these thermal treatment

technologies for on-site, non-sewered, sanitary applications in small scale is reviewed to clarify the specific operational challenges occurring through their implementation. The aim of this study overall is to outline the challenges for developing a suitable technology for on-site sanitary applications and to address optimum ranges of operating conditions for a reliable performance.

2. Sewage Waste/Biomass Treatment Technologies

2.1. Anaerobic Digestion

Anaerobic digestion is a biological conversion process of organic compounds in an oxygen-free environment, producing biogas using microorganisms. The ability to utilise organic feedstock with a high moisture content without reducing the calorific value of the produced biogas is a major advantage of this technique. However, the reaction time ranges from 7 days to 5 weeks and the conversion efficiency of organic constituents from 30–60%; this is not sufficient for agricultural applications regarding their high organic content and poor biodegradability [17]. Digestate from the anaerobic digestion of sludges is still likely to pose biohazardous and other risks due to microplastics [12]. In addition, the volume of the treated sludges through biological means is observed to reduce only 5% of the original mass of sludge [18]. Dewatered sludge can be directly fed into the digester for biogas recovery; however, the high organic content of the digestate has emphasised the utilisation of a pre-/inter- and/or post-treatment step for maximum energy recovery and volatile organic conversion [19].

The overall aim of sludge treatment is to achieve the effective elimination of organic matter and a high recoverable energy content of sludge (11.10–22.10%) [20]. Therefore, thermal treatment technologies have proven to be attractive for resource and energy recovery, treatment and disposal of sewage sludge (SS).

2.2. Conventional Combustion

Thermal treatment processes include combustion and the emerging gasification and pyrolysis technologies. In comparison to anaerobic digestion, thermochemical conversion routes provide much shorter reaction times for the treatment of sludge (seconds to minutes). However, these processes require sludge with a lower moisture content where the decomposition of >90% of the organic matter occurs in the presence of a surplus oxygen, partial oxidising or anoxic (minimised oxygen) environment.

Combustion is used for medical and municipal waste [21]. Combustion is currently used for heat recovery from sewage sludge with the incorporation of a heat recovery step in the treatment process, but the traditional practice was only intended for a reduction in the volume and the elimination of harmful elements [22]. Combustion takes place at high temperatures (800–1150 °C) in the presence of surplus oxygen for the complete oxidation of organic matter, which delivers the transformation of carbonaceous materials into a flue gas consisting of oxides of carbon, nitrogen, sulphur and particulate matter, while releasing a substantial amount of heat and other trace gases and H₂O. Multiple hearth furnace (MHF) and fluidised bed (FBF) are the two common reactor types utilised for sewage sludge combustion, of which the MHF is suitable for wet sludge while the FBF is used for both wet and dried sludge. A major barrier for the cost and process efficiency of sludge combustion is the moisture content of sludge with the acceptable limit of <50% [23]. Hence, dewatered sludge undergoes a drying step after the dewatering stage to increase the calorific value of the fuel for thermal processing [20]. A high moisture content results in incomplete combustion as well as heat loss from the evaporation of the moisture content [23]. Additionally, it reduces the energy content of the sludge to 4 MJ/Kg (60–80% moisture content), which is inappropriate for autothermal combustion [24]. Therefore, this process is usually associated with the utilisation of auxiliary fuel and catalysts for the initiation and further reaction stability. This process offers a reduction of up to 90% in the volume of sludge, leaving an inert material (ash) for disposal. This is a potential product and could be used for the production of building materials [15]. A high ash content

in SS is also thermally parasitic, which leads to incomplete combustion, thus forming a variety of pollutants such as polycyclic aromatic hydrocarbons and dioxins [25]. The high inorganic constituents in sewage sludge ash such as alkali-induced metals also cause further challenges such as slagging and agglomeration. A major challenge for the combustion of sewage sludge is the elevated amount of NO_x , SO_x , etc., which could be sourced from human activities (e.g., faeces) [26]. Different researchers investigated the pollutant emission of sewage sludge combustion, concluding a reduction in the concentration via lower combustion temperatures [20] and co-blending [27] for NO_x and SO_x , respectively. In a study by Han et al. [23], it was observed that SO_2 could also react with the water in the wet sludge and lead to the formation of H_2SO_3 , a corrosive compound for metal surfaces. Although analysis on the concentration of heavy metals in the past studies on SS combustion revealed modest percentages below legal limitations, these studies still implicated the utilisation of efficient gas cleaning systems to capture the heavy metals present in the particulate matter and highly volatile species (e.g., Hg, Cd and Pb) in the vapours [28,29]. To address the problems mentioned above, recently there has been an increasing interest in an emerging method named ‘co-combustion’ by combining sewage sludge with other high-rank energy fuels such as biomass and coal [25].

2.3. Emerging Methods

Although combustion leads to a major reduction in the volume of sludge, the large amount of flue gas generated through the process incurs a high cost for their treatment as well as high energy consumption for pre-drying. Wand et al. [30] reported that the development of co-combustion with a slight modification in conventional combustion equipment for sludge has taken precedence over pyrolysis, gasification and mono combustion in large scales.

2.3.1. Co-Combustion

Co-combustion has been considered as a new route for net CO_2 reduction in sewage sludge valorisation. The utilisation of co-combustion/blending has mainly aimed for improving combustion reactivity and reducing pollutants and greenhouse gas (GHG) emissions. In a study by Rong et al. [31], a synergetic interaction between the rice husk and sewage sludge co-combustion was observed, while the reactivity between the blends was improved when the SS proportion remained <30 wt.%, resulting in the production of an ash with lesser slagging potentials. Moreover, Wang et al. [30] investigated the combustion behaviour of sewage sludge (SS) and wheat straw (WS) co-blending, where the combustion characteristics of SS were enhanced with the highest synergetic interaction in the presence of 50% WS.

2.3.2. Advanced Thermochemical Treatment (ATT)

The thermochemical conversion of sewage sludge is a promising alternative to biochemical practices due to its ability to decompose almost all organic parts (biodegradable or non-biodegradable) in a short period. In addition, there has been great interest towards the valorisation of sewage sludge and municipal waste into oil and synthetic gas via pyrolysis and gasification [22]. Advanced thermal treatment technologies are also capable of reducing the volume of waste, degrading hazardous organic matter and recovering hydrocarbon compounds from the residues rather than heat only. Additionally, the risk of producing dioxins, furans, SO_x and NO_x could be mitigated via restricting the environment in ATT processes [8].

Pyrolysis

Pyrolysis, together with the evaporation of bound moisture, is an initiating step in all thermochemical conversion processes occurring at moderate temperatures (350–600 °C) in an inert (non-reactive) environment. The decomposition of SS (organic matter) through this process results in the production of liquid pyrolytic oil (condensable volatile fraction),

pyrolysis gas (non-condensable volatile fraction) and char (solid residue) [32]. The liquid pyrolytic oil has been upgraded for combustion in boilers or engines as well as electricity production [33]. The biochar derived through pyrolysis has been utilised as a solid fuel, an adsorbent for decontamination, a fertiliser for soil amendment and briquetting [14,34,35]. However, the char from sewage sludge has not been found suitable for heat recovery owing to its low heating value (5 MJ/kg) as well as the presence of a high concentration of heavy metals, which restricted its landfilling [32]. To address the challenges with the utilisation of char, researchers have focused on improving the quality of the char for soil productivity and the remediation of contaminants via feedstock chemical impregnation [36]. The syngas generated through thermal cracking of the tar in high temperatures (secondary reactions) is used in internal and industrial combustion engines [37]. Depending on the various operational parameters such as the heating rate and residence times, pyrolysis is classified into three main categories, namely slow, fast and flash pyrolysis [38]. Slow heating rates (0.1–1 K/s) and long residence times favour the formation of char [34], while lower or higher residence times in high temperatures with high heating rates result in liquid and syngas production, respectively [17]. Table 1 illustrates the process conditions in different pyrolysis modes where the residence times of volatiles for slow/intermediate, fast and flash pyrolysis are 10–30, <2 and 0.5 s, respectively [39]. Conventionally, fast pyrolysis has been used to produce pyrolytic oil, whilst slow/intermediate pyrolysis has favoured the formation of char and non-condensable combustible fractions. High heat influx involved with fast pyrolysis, as well as substantial heating rates for the rapid decomposition of dry matter, faces complexities regarding the pre-processing of the feedstock. Pre-processing includes operations such as particle size reduction and efficient drying to a range of 10% moisture content [40]. Park et al. [41] observed that larger particles in the sewage sludge led to incomplete fast pyrolysis due to a lack of uniformity. The liquid pyrolytic oil, especially the organic fraction, from fast pyrolysis contains a high heating value of ~33 MJ/kg, which makes the fast modes of more interest compared to slow pyrolysis. Hence, most previous research focuses on the production of bio-oil within fast pyrolysis of sewage sludge [22]. The production of pyrolytic oil through this process requires fast vapour removal and quenching to mitigate the chance of secondary reactions, resulting in the breakdown of longer chain species with high molecular weight to light gaseous products [41].

Table 1. Classification of pyrolysis process [38,42].

Pyrolysis Process	Temperature (°C)	Heating Rate (°C/min)	Solid Residence Time (s)	Particle Size (mm)	Product Yield (%)		
					Oil	Gas	Char
Slow/int	400–500	10	~500	5–50	30	35	35
Fast	400–650	100	0.5–10	<1	50	20	30
Flash	700–1000	>500	<0.5	<0.2	75	12	13

Product diversity and distribution are mainly dependent on process temperature, operational modes, reactor configuration and feedstock characteristics [43]. Different reactor designs have been established for pyrolysis depending on the desired final output (e.g., heat, electricity, liquid, syngas and/or char) as well as feedstock characteristics. For instance, fluidised bed reactors have been found suitable for the fast pyrolysis of biomass in commercial applications regarding their good temperature control and efficient heat transfer [39,42].

The chemical reactions taking place during pyrolysis are endothermic and are pursued in an inert (non-ignition) environment by means of external heat source. Hence, to address the energy intensity of pyrolysis, research on the partial/complete combustion of syngas and pyrolytic oil for the self-sustainability of this process has been carried out [44,45]. Since the desirable product from pyrolysis (mainly fast and flash modes) is the bio-oil, <10% moisture content [18] in the feedstock has been considered suitable for fast pyrolysis,

which implies greater energy consumption for pre-drying in comparison to combustion. A high water content has been known to be disadvantageous for the energy content and combustion characteristics of bio-oil [46]. Although the pyrolysis of raw sludge (MC of ~70–80 wt.%) leads to a significant condensed water fraction in the bio-oil, this method has been found to be suitable for the generation of hydrogen-rich non-condensable gases via in situ steam reforming of the volatile compounds and partial gasification of the char [47]. Dominguez et al. (2006) stated that the pyrolysis of wet sewage sludge provides a higher gaseous fraction with significant hydrogen content within the combination of pyrolysis and gasification due to the presence of water in the reaction atmosphere compared to the pyrolysis of dried sludge [48]. To conclude, high water content as a major challenge for the production of bio-oil cooperates with the self-sufficiency issues of pyrolysis for the limitation on the commercialisation of pyrolysis. However, opportunities for the usage of pyrolysis in large resource recovery applications from dried sludge are predicted [32].

An advantage of pyrolysis over combustion and gasification is that the emissions include lesser pollutants (e.g., heavy metals, dioxins, furans). Conesa et al. (2009) investigated the effect of temperature and oxygen on the emission behaviour of different wastes including sewage sludge, where it was observed that the concentration of furans was increased along with an ascending oxygen ratio [49], whereby polyaromatic hydrocarbons (PAHs), which were formed through pyrolytic conditions, followed a negative trend with the oxygen increase. Analysis on the temperature effects also revealed a maximum point at temperatures of about 750–850 °C under pyrolytic conditions. In contrast, the PAH concentration under combustion conditions was also maximised at ~800 °C. This could indicate less pollutant emission because of the lower operating temperature of pyrolysis. Moreover, Jin et al. (2016) analysed the behaviour of heavy metals during the pyrolysis of sewage sludge and concluded the retention of the majority of them in the char, resulting in enhanced bioavailability and thus lower risk to the environment [34].

Gasification

Gasification is an extension to the pyrolysis process in which the resultant gas and solids (char) from pyrolysis undergo further reactions in the presence of 20–40% oxygen needed for combustion. The temperature through this process ranges from 700–1000 °C, where the formation of light combustible gases (syngas), such as H₂ and CO and other gases (i.e., CO₂, CH₄), from the gasification of the carbonaceous content (char) takes place [14]. This process involves two more core stages after drying and pyrolysis, where the partial oxidation of the char and volatiles takes place involving a gasification agent such as air, CO₂ and steam or a combination of these (e.g., air–steam or steam–O₂). These stages result in the gasification/reduction of the char via the heat generated from the exothermic oxidation reactions in ~1100 °C. The resultant heat from the partial oxidation stage also supplies the energy for drying and pyrolysis, which implies the self-sustaining behaviour of the process. However, the acceptable moisture content limit suitable for in situ drying of SS during gasification is less than 20 wt.% [17]. Moreover, due to restrictions on the reaction environment, the formation of SO_x, NO_x, heavy metals and other aromatic compounds is minimised [32]. The syngas obtained from this process is typically used for heating or electricity generation, or further processed for chemical or liquid fuel synthesis [22].

The product yield, quality and the process completion because of complex sequential thermal decomposition reactions in various stages throughout the process are dependent on the gasification medium, gasifier type, reaction conditions and feedstock composition. Among several types of gasifier configurations, fixed-bed downdraft, fixed-bed updraft and fluidised bed reactors have been investigated for sewage sludge [22,50]. The difference in an updraft and downdraft configuration is mainly in the introduction mechanism of the gasification agent into the reactor. In an updraft configuration, the gasification agent enters the reactor from the bottom and the feedstock falls from the top, resulting in rapid oxidation of the char from pyrolysis reactions. Following that, the hot gases exit the reactor from the top, potentially carrying high concentrations of tar. However, in a downdraft configuration,

the gasification medium is introduced from the side, which descends within the contact with the pyrolysis products. This configuration facilitates the reduction mechanism of the char via further heat transfer in the char bed. The overall energy efficiency of the updraft design is higher compared to the downdraft design, owing to the efficient heat transfer between hot gases between volatiles, char and sludge in the reduction, pyrolysis and drying zones, while the hot gases exit the reactor in high temperatures. However, the tar content of the syngas (producer gas) as a bulk criterion is lower in comparison to the updraft design [40]. Although keeping moisture content in the range of >20 wt.% is preferable due to heat losses and the energy consumption of water vaporisation during gasification, the two reactor designs can handle higher moisture contents up to 50% in optimum reaction conditions [22]. Moreover, fluidised bed reactors have been utilised to address the challenges regarding uniform heat transfer and temperature distribution in the reactor via introducing the gasification medium in a suspended form fluidising gas.

2.4. Review of Comparative Assessment Studies

Several researchers have published comparative studies on the thermochemical conversion of sewage sludge to aid in the selection of a sustainable technology for sewage sludge management [17,32,51]. The objective of these publications has been to review the literature and compare the thermochemical conversion technologies either qualitatively or by using a comparative method (SWOT, FAHP, etc.). However, the conclusions from these studies differ since various technical criteria are applied in each study. The ranking mechanisms in previous studies are affected by the environmental regulations and technological development corresponding to the geographical zone in which the study was carried out. A critical review of these publications indicated that among combustion, gasification and pyrolysis as the main thermal treatment routes, pyrolysis could potentially provide a more sustainable approach towards sewage sludge management. This finding is a result of reduced pollutant emissions and zero hazardous waste disposal goals achieved through this technology. Nonetheless, the advantage of this technology is offset by intensive energy consumption for pre-treatment/drying that needs to be addressed to fulfil sustainability goals [32].

2.5. Review of Micro-Scale Human Faecal Sludge/Faeces Treatment Studies

Recently, there has been a great shift in interest towards the utilisation of small-scale thermochemical conversion technologies for sanitation [52,53]. The on-site sanitation approach for non-sewered communities (low-income countries) or parts of developed countries where sewage infrastructure is inaccessible/difficult is identified to aid in the promotion of faecal sludge management [54,55]. Some of the features of this approach are restrictions on the finances for storage and transportation, potential energy recovery from natural resources and mitigation of the risk of non-optimal disposal of human faecal waste in the environment. Indeed, the physical and chemical characteristics of the solid waste (mainly faecal matter and/or tissues) generated and stabilised through these decentralised wastewater treatment systems are different from those stabilised in commercial/pilot-scale wastewater treatment plants. Most of the research in this area has been conducted in response to initiatives such as Bill and Melinda Gates' 'Reinvent the Toilet Challenge' (RTTC) [2,3,56]. The innovative sanitary systems built under this initiative are required to operate in a waterless mode, whilst pursuing sustainable operation from the energy intensity point of view by recovering energy from solid waste [52]. Meanwhile, the micro-scale thermal processing systems in these contexts are designed to handle human waste in households of ten people considering the average input rates of 200 g per capita per day [52]. In response to this initiative, researchers at Cranfield University developed a novel sanitary system 'Nano Membrane Toilet' (NMT), for which extensive research on the utilisation of thermal treatment methods for human faeces was undertaken [52,54,55,57].

The gasification of dry and moist human faeces via thermodynamic modelling at the optimum equivalence ratio (ER) has been investigated [57]. Authors observed a decline in

the content of exergy obtained from moist faeces (max 15 MJ/kg) at the optimum equivalence ratio and temperatures compared to dried samples (24 MJ/kg). The high moisture content of faecal samples was identified as 'parasitic' to gasification since the optimum point for thermal cracking was studied to be near combustion conditions (equivalence ratio of 0.55–0.62). As a result, the heat generated through gasification was absorbed by water vaporisation reactions and the ignition and subsequent conversion processes were delayed. Overall, this study reveals the exergy deficiency of moist faeces' gasification, as the generated heat and the exergy of the syngas were not sufficient for in situ drying, implying the necessity of energy-intensive pre-drying of the feedstock.

In another study, a bench-scale downdraft combustor was used to evaluate the optimum conditions for converting faecal biomass to energy through combustion [55]. The combustion characteristics of dry and moist faeces were evaluated under different conditions (i.e., air-to-fuel ratio, moisture content, etc.). Preliminary results from the combustion of simulant faeces showed a moisture limit handling of 60% with a bed temperature of 600 °C. The optimum combustion conditions for various dried faeces were characterised as (1) a minimum bed temperature of 600 °C and (2) 16 L/min airflow rate. The tests were performed using 50–75 g of wood biomass to ensure the optimum bed temperature followed by an addition of 50 g of faecal samples. However, the results revealed the failure of the tests in the case of moist faecal samples due to the non-definite form of faecal samples. Different shrinkage rates in faecal samples representing different moisture contents were observed to result in the partial drying of faeces without ignition. To confirm, this physical characteristic of human faeces was found to decrease the front combustion velocity dramatically from 2.18 to 0.72 mm min^{−1} where shrinkage was high [58]. Evaluation of the effects of fuel pellet size during combustion by [55] indicated a poor carbon conversion efficiency and a reduction in the process temperature attributed to improper interaction between the biomass material and hot air.

Findings from the study by Onabanjo et al. (2016) were used to successfully commission a novel micro-combustor capable of operating in downdraft and updraft modes under continuous feedstock flow conditions [54]. In contrast to the 2016 study, the continuous mode of operation was followed to limit the energy requirement for ignition and to keep the combustion bed at a sufficient temperature for incoming faecal material. The aim was to convert human faeces with the lowest possible temperature to ensure energy efficiency and to reduce the heat loss through combustion. Ultimately, the heat generated was used for the pre-drying of the feedstock or the other energy consumer with the NMT concept. The optimum temperatures for sustained fuel ignition and steady-state operation of the reactor were estimated as 220–240 °C for dried faeces and were generated using an air igniter. The authors stated that the spark device as a part of the ignition system was not necessary as the temperature reached 400 °C. The dominant challenge with the self-sustainability of combustion was the fuel feeding rate at this small scale, which caused two operational problems:

Incomplete thermal conversion as the interval between each feeding was delayed for longer than 2 min, mainly due to the scale of the process with an optimum 1.2 g/min feed rate;

Blockage in the feeding system due to char production at the reactor's inlet; The authors suggested that further research for the optimisation of the micro-combustor for self-sustained combustion should be carried out [54].

A summary of the reviewed benefits and drawbacks associated with the main sewage waste stabilisation technologies throughout this study is provided in Table 2. The contents aim to highlight the overall performance of each technology, implemented in various scales, to facilitate the selection of a method for the decentralised treatment of human waste in micro-scale sanitary applications.

Table 2. Pros/cons of sewage waste stabilisation methods.

Main Sewage Sludge Stabilisation Methods				
Biological		Thermochemical		
Anaerobic Digestion (AAD)	Combustion	Gasification	Pyrolysis	
Advantages • High water content of solid waste has no impact on the calorific value of biogas • Cost efficient technique • Simple by-products for end-use (Methane for energy recovery and stabilised sludge as fertilizer)	• Major reduction in the sludge volume (90%) • Complete pathogen removal and sterilization • Chance of energy recovery	• High efficiency energy recovery • Lower environmental emissions due to production of ‘cleaner’ syngas • Major volume reduction • Complete pathogen destruction and sterilization	• Takes place under inert environment—no need for auxiliary fuel • Pathogen removal and sterilization • Low sensitivity to the feedstock physical properties • Low emissions due to absence of oxygen • Retention of inorganics and metal content in the char fraction • Lower heat fluxes—robust reactor operation • Chance of energy recovery from products	
Disadvantages • Very long processing timeframes • Limited conversion of organic matter (30–60%) and poor energy recovery • Non-efficient elimination of hazardous fraction in sludge • Limited reduction of sludge volume	• Lack of regulations • Requires ignition with the aid of auxiliary fuel • Needs fuel pre-treatment and moisture reduction • Extensive emission control needed • Operational complexities due to the ash and particulate matter • Very high heat fluxes with reaction area	• Need for moisture content reduction • High sensitivity to the physical properties of the feedstock • Need for ignition—auxiliary fuel • High heat fluxes present in the reactor • Inadequately practiced • Need for gasification agent—constraining implementation • Tar production	• Requires fuel pre-treatment (drying) • Energy intensive process • Inadequately practiced • Delivers by-products to be handled • Lack of regulation	

3. Discussion

A critical review of previous work completed on the subject of thermochemical treatment reveals the technical challenges associated with the implementation of 3× main thermochemical processes for various types of biomass and waste materials. Furthermore, a detailed analysis on the research completed for the development of on-site sanitation technologies highlighted the necessity of highly accurate process control and the optimisation of gasification/combustion. This has been due to the need for proper in situ ignition of the fuel, which is highly sensitive to the moisture content, feedstock flow rate, fuel physiochemical characteristics and the design of the reactor. Hence, the suitability of thermal conversion systems for sanitation depends on the capability of the system to handle alternative feedstock flow rates with different shrinkages and moisture contents. In this study, pyrolysis is selected as the promising method for on-site sanitary applications, and further on, a comprehensive discussion on these processes will be conducted. Overall, research on the thermal conversion of human faecal waste is very scarce and a huge gap on the optimisation, emission rates as well as net energy balances of these processes remains in the literature.

3.1. Energy Consumption

The thermochemical conversion routes practiced commercially for sewage sludge as the most similar material to human faecal waste and other biomass types are depicted in Figure 2.

For a combustion process, the chemical reactions corresponding to each step occur sequentially with some overlaps delivering different inputs for the following step with various energy contents. However, these processes are well distinguished from one another owing to the presence of oxidising agents in different concentrations during each stage [59]. Hence, the net energy balance analysis of each thermal treatment process is different and difficult to be compared with others regarding the: (1) complex sequential endothermic and exothermic reactions and (2) the variety in the energy content of the products in the

outputs. It is notable that a positive/negative net energy balance for these processes does not consider the drying process. The initiating drying process is a complete endothermic step for the vaporisation of the water content in biomass/waste requiring a substantial amount of energy, such as 3.4 MJ/kg in typical dryers with non-unity efficiency [60].

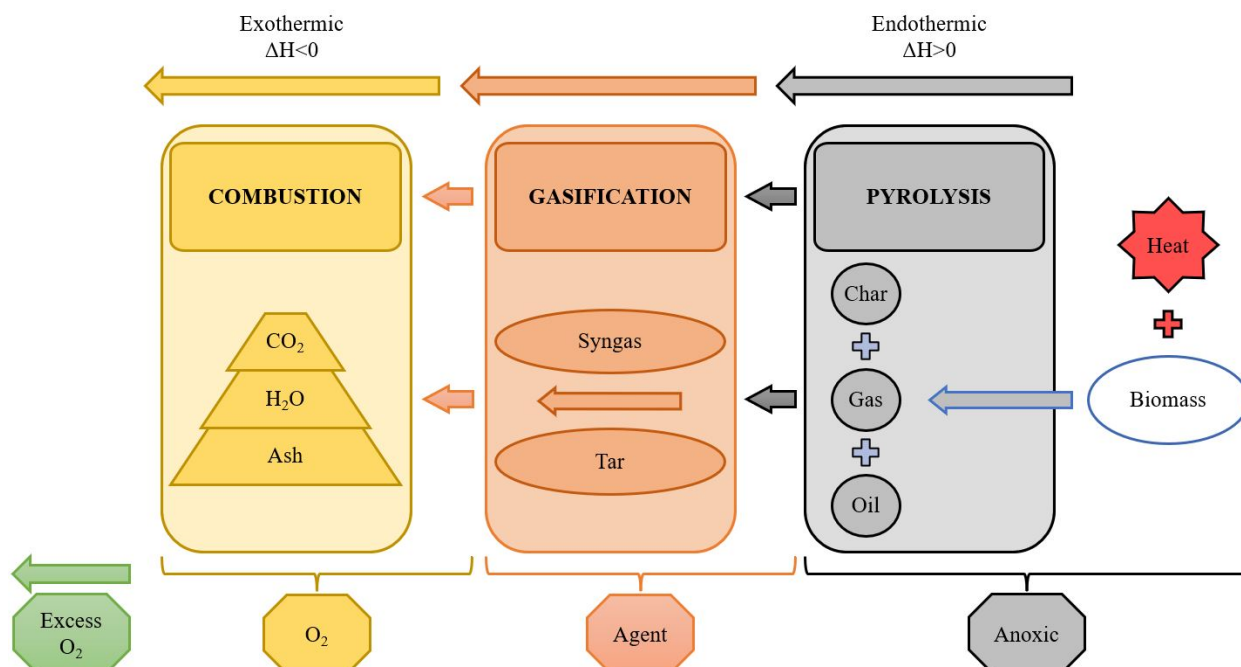


Figure 2. Three common thermal treatment routes [58].

In the context of sanitary applications, for the implementation of a successful thermal conversion system in an application where extraneous energy is available for the completion of treatment, pyrolysis could still be an option. As depicted in Figure 2, pyrolysis is an energy-intensive process in contrast to gasification and combustion since the endothermic non-spontaneous reactions are predominant in this step/process. In the case of sewage sludge, pyrolytic reactions were found to be mostly endothermic in the order of 100 kJ/kg, whereas the exothermicity of oxidative reactions was found to be in the order of 10,000 kJ/kg [61]. To further elaborate, net energy positivity/negativity could be defined as the energy released from the exothermic reactions or available in the energy-rich products of each process, being less than, equal to, or more than the energy needed to complete the endothermic reactions in each process.

For pyrolysis, researchers have explored the sensible heat to bring reactants to pyrolysis temperature, the heat of pyrolysis and the sensible heat for product evolution, all together known as the enthalpy for pyrolysis [62], for different types of biomass and sewage sludge using different methods, shown in Table 3. Daugaard et al. [63] estimated the enthalpy for two types of wood as well as two herbaceous materials ranging from 0.8 ± 0.2 MJ/kg for oat hulls to 1.6 ± 0.3 MJ/kg for pine. The method utilised in this study covered a comprehensive analysis on the energy inputs and outputs within the reactor accompanied by inaccuracies in the estimation of heat loss within the range of 16–17.5%. In another study, the heat for the pyrolysis of birch dowels in dry and moist (55 wt.%) conditions was determined as 2.9–3.5 MJ/kg and 8.1–8.6 MJ/kg [62]. Further studies investigating the enthalpy for the pyrolysis of biomass and waste are summarised in Table 3.

Table 3. Enthalpy values and net energy assumptions for the pyrolysis of various biomasses and sewage sludges.

Waste Type	Enthalpy (MJ/kg)	Moisture Content (%)	Description	Reference
Oak	1.46 ± 0.28	8.0	Pilot-scale fluidised bed pyrolysis reactor operating at about 500 °C.	[63]
Oat hulls	0.78 ± 0.20	10.2		
Pine	1.64 ± 0.33	7.5		
Corn stover	1.35 ± 0.28	8.8		
Birch dowels	2.9–3.5 8.1–8.6	0 55	‘Water tracer’ technique was applied for the determination of the time of pyrolysis for a dry and an identical moist particle. However, this non-conventional method is known to result in errors within calculation [63].	[62]
Wood chips	0.7	5.9	The analysis of the enthalpy of pyrolysis was performed on a multiple-hearth reactor. An empirical method ‘P.D.U.’ was used to indicate the difference between electric energy consumption prior and through wood feeding.	[64]
Cedar, Pine, Willow, Bamboo, Sasa bamboo	1.3 ± 0.2 1.5 1.5 1.5 1.6	0	Enthalpy for the pyrolysis of five different types of biomass materials was calculated using a screw feeding reactor. The analysis aimed for the determination of the enthalpy of the formation of products based on their composition. However, the method used for the enthalpy of bio-oil included errors.	[65]
Willow chips	1.17	9.1	Analysis on conventional and MW pyrolysis (required electricity).	[66]

Recently, several studies reported a self-sustainable pyrolysis to be achievable through theoretical combustion of the pyrolytic products. Typically, a low heating value of the non-condensable fraction has made it more suitable for heating the unit [67]. For sewage sludge, McNamara et al. (2019) found the energy content of pyrolytic gas and oil to be always sufficient for the pyrolysis process using the theoretical heat capacities of the constituents [60]. In another study of sewage sludge pyrolysis [68], the available theoretical heat of combustion for domestic sewage sludge was determined as 825 kJ/kg. This suggests higher recoverable energy from the non-condensable fraction of syngas in comparison to the heat required (730 kJ/kg) for the pyrolysis of the same type at 500 °C. For the two other types, excessive energy through the combustion of the bio-oil fraction was suggested for the self-sufficiency of the process. However, the analyses were all performed on dried sludge solids with 5.7% moisture content. Furthermore, analysis on the five different types of dried biomass by [67] indicated a self-sustainable pyrolysis to be feasible. The available enthalpies for pyrolysis in the literature in a range of 6–15% of biomass HHV were used. The authors observed that, considering the upper limit (15% HHV of biomass) as the enthalpy for pyrolysis, the process gas yielded at a high treatment temperature of 650 °C could only surpass the enthalpy in some cases.

Taking the completed analyses on the energy efficiency of pyrolysis into account, the commercialisation of pyrolysis is still criticised by some researchers. Rollinson and Oladejo (2019) stated that a self-sustainable pyrolysis process is practically implausible and thermodynamically unproven. The authors highlight the importance of considering pre/post-treatment energy demands as well as proper thermodynamic considerations repetitively [69].

In the context of sanitary applications, addressing a gap on the heat required for the pyrolysis of human faeces/faecal sludge is necessary. This could be followed by an analysis

on the conditions to produce maximum yields with the highest calorific value of py-gas and py-oil to address the net energy balance of this system. In a study on the pyrolysis of human faeces, Yacob et al. (2018) investigated the effects of heating rate and HHT on the yield and energy content of the non-condensable fraction of syngas (py-gas) including CH_4 , CO , CO_2 and H_2 as well as ethane. The promising conditions were evaluated as an operating temperature of $450\text{ }^\circ\text{C}$ and a heating rate of $2.5\text{ }^\circ\text{C}/\text{min}$, which provided $22.8\text{ MJ}/\text{Nm}^3$ and 29.6% gas mass yield, respectively [53]. However, in this study the analysis was performed on dried human faeces. To limit the energy consumption of a system implemented for sanitation, the recoverable exergy of syngas is of concern. An analysis on the total exergy of the syngas from the gasification of human faeces showed that moisture content could increase the exergy from 19 to $22\text{ MJ}/\text{kg}$ at an ER of 0.55 [57]. The moisture content limit was also observed to increase within progressive ER but at the expense of total exergy loss of the syngas, up to a point beyond which the exergy potential reached a lower extent than the gasification of dry faeces at the optimum point. Hence, the operating range at which the pyrolysis system can accommodate the highest moisture content is essential to reduce the energy needed for pre-drying.

Lastly, the pyrolytic char produced from such a system could also be used for energy recovery through combustion. To maximise the yield of the non-condensable fraction, high heating temperatures are required. Analysis on the product distribution of different biomass types showed a higher yield of combustible species such as H_2 and CH_4 occurring at temperatures $x > 550\text{ }^\circ\text{C}$ in most cases with a lower heating rate [67]. In the case of human faeces, this operating range was at $\sim 550\text{ }^\circ\text{C}$ [53]. Though at this HHT, the yield and energy content of the char reduce to half [67]. Ward et al. (2014) observed the faecal chars made at $750\text{ }^\circ\text{C}$ having $13.8 \pm 0.48\text{ MJ}/\text{kg}$, which was much lower than those made at $350\text{ }^\circ\text{C}$ with $25.6 \pm 0.08\text{ MJ}/\text{kg}$ [70].

3.2. Technology Development

Prioritising a solution to address the issues observed with the energy intensity of a pyrolysis system, the operational reliability of the system needs to be considered carefully to ensure a safe and continuous functionality. This would then allow the transfer of such a system, not only for on-site processing in non-sewered applications, but also for mobile applications where the least maintenance is desirable. To achieve this, a novel design for the pyrolysis system should be proposed to meet the expectations regarding the energy intensity, technology robustness, application constraints and the safe disposal/emission of its by-products. The innovative design of such a pyrolysis system should include an immediate energy recovery step from the by-products, overly controlled by various factors such as the fuel properties, the process conditions and the mechanical design. These factors are interrelated where the immature selection/planning of each could lead to the improper processing of waste, malfunctioning of the reactor, mechanical fatigue or ultimately the infeasibility of the technology for the application.

For a proper energy recovery sub-system, the production of non-condensable fractions would be of more interest to facilitate the product's (non-condensable and condensable fractions) combustion in the afterburner/atomiser. Researchers have reported many more constraints for the combustion of bio-oil in comparison to syngas, where the high water content in the vapour phase has been found to reduce the energy density, the adiabatic flame temperature, local combustion temperature and combustion reaction rates [46]. In addition to the water content, the presence of solid particles (ash, etc.) and other physical properties could complicate the atomisation and lead to erosion in the pipeline. A previous study reported that sustainable combustion could not be achieved through bio-oil since the slight flash in the compound is suppressed by the evaporated water [71]. Furthermore, refractory behaviour observed with the long-chain molecular hydrocarbons complicates the thermal processing of them as well as the high oxygenate content leading to instability and higher viscosity [72]. Overall, through a novel chemical process design, the production of more syngas through pyrolysis followed by immediate energy recovery could provide

the potential high temperatures for the ignition of bio-oil in the vapour phase. Some of the core parameters affecting the product distribution and properties will be discussed further to provide an insight on the optimum operating conditions of such a system.

To further elaborate, the term ‘operational reliability’ of such a system points out the production of a suitable gaseous fraction (both non-condensable and condensable) for rapid combustion and energy recovery. For syngas, as the focus of this study, delivering the highest reactivity for ignition and laminar flame speeds is vital for a reliable combustion performance in the after burner/atomiser. Research on the ignition and combustion properties of various blends of gaseous fuels indicate that the higher the H_2 content, the more O, H and OH radicals are released, enhancing the chain branching, propagation and termination reactions [73]. The presence of these radicals promotes the consumption of hydrogen, C_1 and C_2 – C_3 fractions, and overall the reaction rates which lead to lesser ignition delays of the fuel. Trials were conducted in high pressures where lower rates of radical production were observed at H_2/CH_4 concentrations of 40/60% [74].

Similarly, in a modelling study using Digital Analysis of Reactive System software (DARS), it was observed that the more CH_4/H_2 there is, the longer the ignition delay time, with the temperature playing a significant role where the change in reactivity was more sensible at lower temperatures [75]. Moreover, the laminar flame speed was reduced as the CH_4 with lower reactivity was increased in correlation with the reduction of H_2 .

Typically, another substantial fraction in syngas is carbon monoxide (CO), which results in the poor ignition of the fuel due to its low combustion rates. Analysis on the thermal efficiency of dual fuel operation of an engine shows that through an increase in the ratio of H_2/CO , an improved thermal efficiency was achieved [76]. However, this was limited to 75:25 as CO oxidation was optimum at this ratio. In addition, the higher H_2 content was observed to increase the flame travel and lower the auto-ignition temperature of the fuel.

Overall, a review of these papers reveals the improved combustion characteristics of syngas within an increase in the H_2 content. However, this would be at the cost of higher generation of NO_x fumes in the exhaust gas due to the presence of higher reactive radical species such as O and OH.

In the further steps, the effects of various consecutive process parameters specifying the evolution of different gas species will be discussed to select an optimum processing condition for such a system. Other than the combustion performance of the syngas, criteria to be considered in the further steps are:

- (1) Limiting energy consumption as much as possible;
- (2) Lesser chances of fatigue, particularly when the least maintenance is feasible;
- (3) Accommodating any incoming feedstock volumes with different physical characteristics;
- (4) Delivering emissions below regulating limits for both solid and gaseous by-products, and;
- (5) Reducing the solid waste volumes in considerable amounts.

3.3. Syngas Yield and Energy Content—A Trade-Off with Combustion Performance, Emissions and Bio-Oil Properties

3.3.1. Temperature vs. Yield

Numerous studies have investigated the effects of various process parameters on pyrolysis products. It is well known that the high heating temperature performs a dominant role on the yield and distribution of pyrolytic fractions [76,77]. Higher temperatures provide sufficient energy for the bonds in biomass to break and achieve a better conversion efficiency [76]. Figure 3 illustrates the trends observed through the pyrolysis of various feedstocks in a few studies.

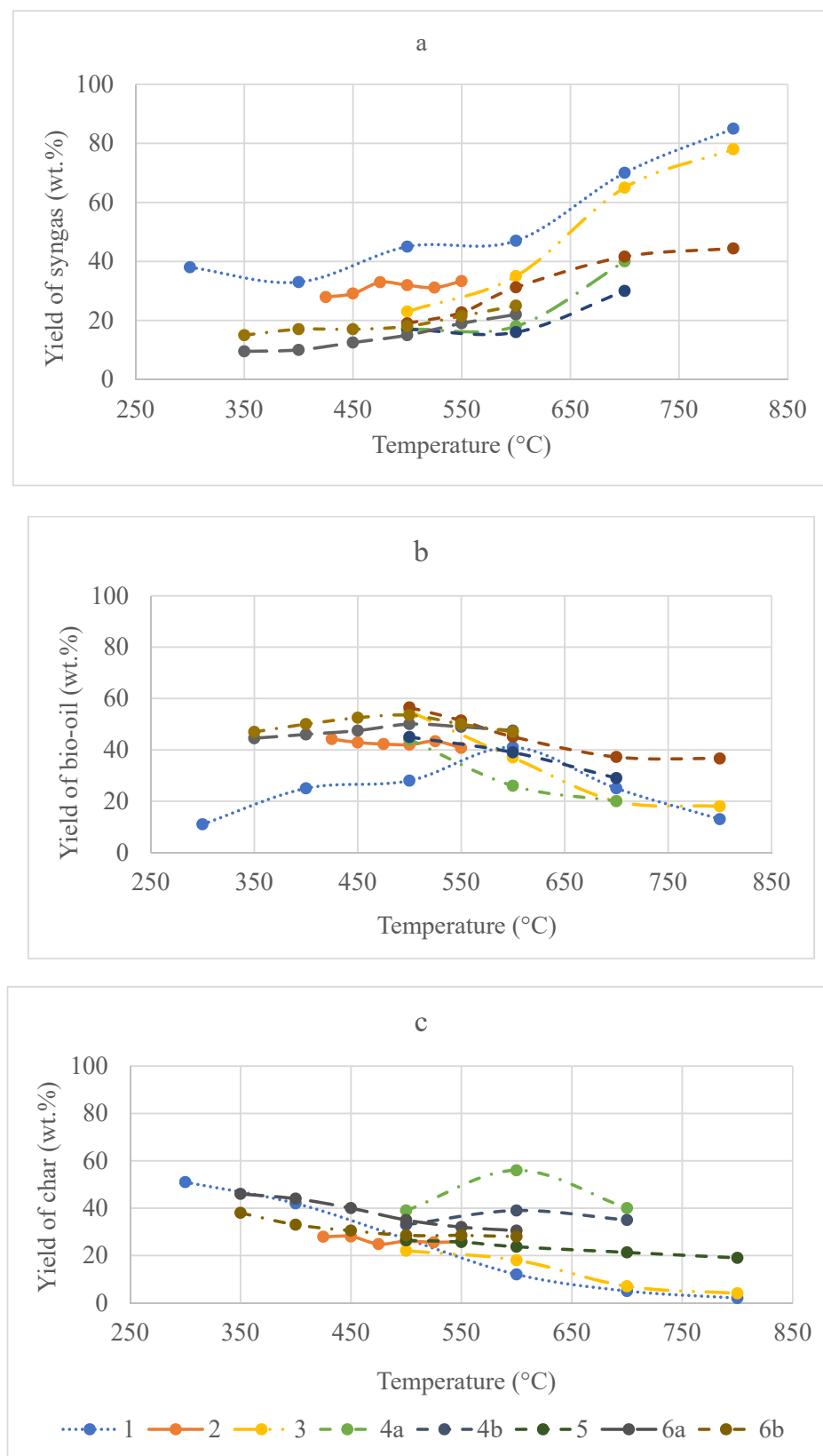


Figure 3. Effects of pyrolysis temperature on the yield of pyrolytic fractions: (a) non-condensable fraction, (b) condensable fraction, (c) residual char: (1) Anaerobically digested sewage sludge [78], (2) Milkweed [79], (3) Legume straw [80], (4a) Corn cob and (4b) Corn stalk [81], (5) Pine woodchips [82], (6a) Rice husk and (6b) Corn stalk [83].

Although the variety of feedstock compositions differentiates the yield of products, a common observation has been the increase in the yield of syngas at temperatures higher than 400 °C with drastic behaviour at 550 °C and further. In contrast, the yield of bio-oil follows the same trend after 400 °C but declines drastically at 500–600 °C and after. This shows the significant gas phase secondary reaction occurring at these temperatures, which is associated with the consistent decrease in the yield of char.

3.3.2. Heating Rate vs. Yield

Analysing the effects of heating rate on the yield, it is well known that the higher the heating rates (fast and flash pyrolysis), the more liquid oil could be produced through rapid extraction of the vapour [84]. However, research shows that for the syngas fraction, the heating rate plays a major role in the progressive generation of syngas during slow/intermediate pyrolysis limited approximately up to 200 °C/min [85]. Research on forestry residues shows that applying higher heating rates yields more syngas up to the point where heat and mass transfer limitations within the reaction area are overcome [86]. The product producer gas will be further discussed in later sections.

3.3.3. Temperature vs. Syngas Calorific Value

To suggest an optimum range of temperatures for such a system to operate at, the energy content of the syngas fraction should also be analysed. Figure 4 shows the calorific values (HHV) of the syngas obtained through temperature variations during the pyrolysis of various types of feedstock in different reactor configurations and operating conditions.

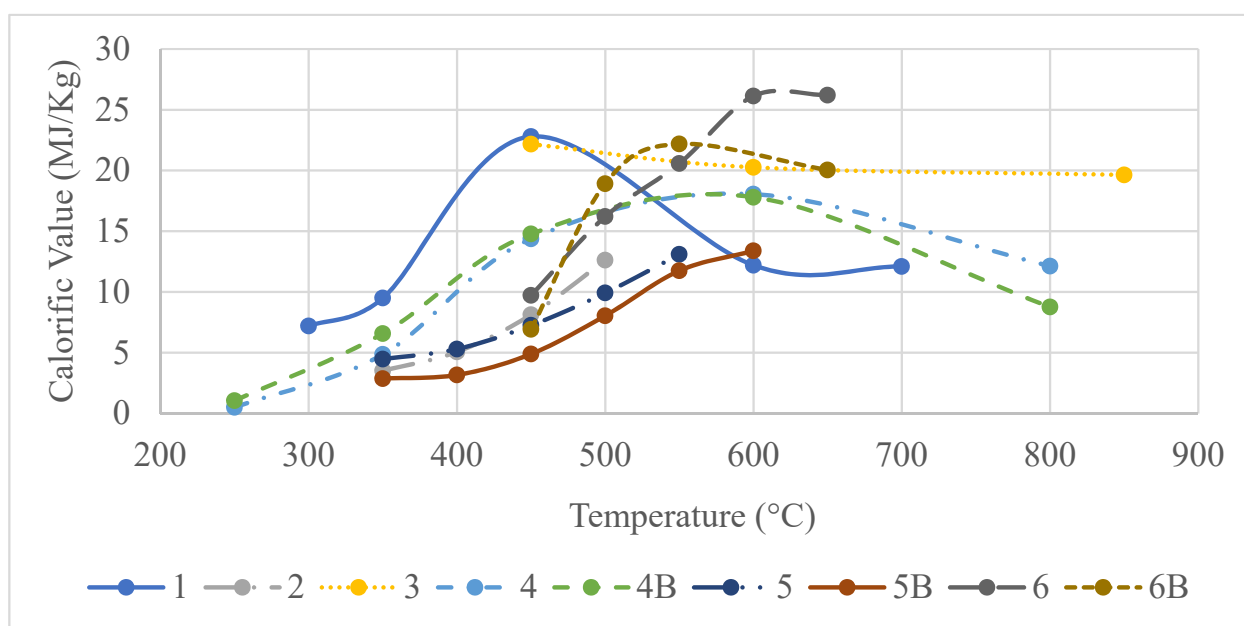


Figure 4. Effects of pyrolysis temperature on the calorific value (HHV) of the syngas: (1) Human faeces [52], (2) Sewage sludge [87], (3) Sewage sludge [43], (4 and 4B) Sewage sludge at 60 and 5 °C/min [88], (5 and 5B) Rice husk and corn stalk [83], (6 and 6B) Dried sewage sludge at 100 and 5 °C/min [89].

The theoretical calorific values in MJ/Kg were calculated using the data on the energy content of each gaseous species reported by NREL [90]. CO, CH₄, H₂, C₂ and C₃ were the only combustible species considered for the comparison commonly reported in all studies, while an average energy content of 65 MJ/Kg was assumed for the last two.

Typically, the most abundant species in the syngas fraction detected in various studies are mainly CO₂, CO, CH₄, C₂–C₃ and H₂ depending on the type of feedstock and process conditions. Clues from pyrolysis practices reveal evidence on the notable increase in the yield of CO and CH₄ at temperatures up to 600 °C and dominant H₂ at further tempera-

tures [91,92]. The production of more hydrogen can deliver zero carbon emissions upon the combustion of syngas, but the operating temperature should be considered carefully with regard to the mechanical design of a system for sanitation where higher chances of fatigue are foreseen at higher temperatures in the structure of the reactor. Moreover, the higher yield of hydrogen leads to the conversion of primary tar from pyrolysis into polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene due to decarboxylation and dehydration [84,91].

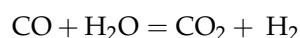
Highlighted in Figure 4, a temperature between 400 and 600 °C during pyrolysis can trigger an upwards trajectory or a peak for syngas energy content for various waste materials. A reason for this is the generation of an energy-rich fraction such as C₂ at 450 °C and maximum CH₄ up to 600 °C [88]. Notably, the trends for the evolution of these gas species in this range of temperatures could be different based on the process conditions, feedstock compositions and reactor configurations [53,93]. Furthermore, the progressive complex consecutive reactions for the generation of each species through pyrolysis and the consequent partial/complete gasification can be found elsewhere [92,94,95].

3.3.4. Heating Rate vs. Syngas Calorific Value

Analysis on the heating rate shows that the evolution of CH₄ and C₂–C₃ species increases through slow/intermediate pyrolysis, resulting in the peak calorific value at lower temperatures [89]. However, the concentration of these species stays almost constant at temperatures of about 450 °C and after [79,82]. Focusing on the generation of energy-rich fractions such as CH₄ and C₂–C₃ fractions at temperatures ranging from 400–600 °C, Gao et al. [89] achieved a higher yield for these species through slow pyrolysis, whilst CO and H₂ evolution showed a peak through fast pyrolysis. In a study of chicken litter pyrolysis, the concentration of CO and H₂ increased at the expense of CH₄ and C₂ due to decarbonylation and steam reforming reactions through fast pyrolysis [85]. As discussed earlier, the increased yield of syngas in a range of heating rates limited between 0 and 200 °C/min could be attributed to the rapid decomposition of tar into gas, where a substantial increase in the concentration of CO and H₂ is observed [96].

3.3.5. Effects of Residence Time (RT)

Considering the residence time as another core parameter affecting pyrolytic product properties and distribution, an almost 50% breakdown of CO₂ is achieved through higher residence times in addition to the reverse impact of high heating temperature as a common observation in almost all studies on pyrolysis [97]. Moreover, prolonging residence times could generate a higher H₂ fraction through the following reaction:



Additionally, Jaramillo-Arango et al. (2016) suggested that enough residence times lead to thermodynamic equilibrium, resulting in H₂ overtaking CO₂ concentrations [78]. A review of multiple studies outlined significant changes in the yield of products achievable through RT variation. This is where the maximum liquid yield is obtained with a lower RT and rapid vapour extraction, whilst prolonging RT leads to the formation of syngas through secondary cracking; both are associated with char breakdown to different contents [82,98]. However, the effects of RT are known to be insignificant on the overall syngas and liquid oil properties but are associated with a progressive decrease in the yield of char limited to the completion of reactions [82,99].

3.3.6. Effects of Feedstock Flow Rate

The throughput of a system implemented for on-site sanitation is highly variable depending on the application, where a high/low frequency of toilet usage might lead to the system's malfunctioning due to a blockage, the improper conversion of waste materials or immature moisture handling within the processing timeframe. Results from an analysis on the feed flow rate show that depending on the design of the system, the vapour residence

times start to decline as the flow rates increase, and consequently a higher bio-oil yield could be generated as the chances for secondary reactions diminish [100]. Detrimental impacts of this parameter in the case of improper design could be the accumulation of tar and particles in the downstream pipeline or a disruption in the operation of the afterburner. A similar phenomenon to the previous citation was observed in a study on the pyrolysis of forestry waste, where insignificant impacts on the surface functionality of bio-oil were recorded [82]. Moreover, the hyphenation of the gas fraction showed that at a constant residence time of 5 min, the CO₂ concentration was decreased as the chances for primary decarboxylation in the reaction area decreased with higher flow rates.

3.3.7. Effects of Initial Moisture Content

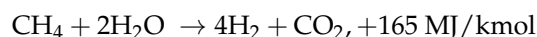
Moisture content has a direct impact on the maximum recoverable energy in such a system where excessive water contents could perform a thermally parasitic role during thermal conversion, which must be considered.

Results from multiple studies confirm that the generation of higher yields of syngas to the detriment of the yield of bio-oil was achieved in most of the cases [78,80,101]. This has been associated with the reduction of char in the system mainly when higher residence times (to conduct reforming) were applied during the process. The governing reactions occurring through the pyrolysis of wet waste materials leading to the partial gasification of organics are [48,59]:

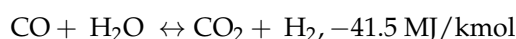
Steam gasification reaction:



Steam reforming reaction:



Water gas shift reaction:



Mei et al. (2020) observed that the steam-rich atmosphere within the reaction area enhanced water gas shift and steam reforming reactions. This resulted in the conversion of pyrolysis intermediate products (liquid oil) to hydrogen, specifically with the catalytic effects of char at higher temperatures of 600 °C [102]. However, temperatures were found to have an insignificant effect on the yields of by-products below 700 °C [47]. This phenomenon was likely due to the difference in the composition of raw materials [48]. Because of the above equations, the concentrations of H₂ and CO₂ have shown elevation, while CH₄ and CO have decreased where the water gas shift reactions were dominant. Consequently, the calorific value of the gas fractions has declined due to the generation of more hydrogen with a lesser energy content compared to CH₄ and C₂ fractions, and so H₂/CO and H₂/CO₂ ratios increased gradually. Further analysis on bio-oil shows that a higher initial moisture content is conducive in the reduction of longer chain hydrocarbons with higher boiling points in the tar fraction (bio-oil) to form lower weight gas species [102]. However, the associated effects of temperature should be disregarded since the production of two or more ring aromatic PHAs is significantly affected at temperatures higher than 600 °C [47].

Finally, the pyrolysis of wet waste materials could enable higher chemical energy stored in the syngas through gasification reactions of the char and steam reforming of the oil [102]. However, an important factor to be considered is the energy recovery efficiency of syngas with alternative moisture contents. The authors observed the suppression of the total recoverable energy from the by-products due to the loss of sensible heat of the products and latent heat of residue steam vapour [102]. This study investigated the syngas

properties within a separate reforming section where the authors demonstrated that a moisture content of 40% delivered the highest energy recovery efficiency of 44.18% from the syngas. The heat consumption for the evaporation of the water content, which does not take part in thermochemical reactions, was found as a possible reason for this.

4. Conclusions

This review followed two comprehensive objectives, further mentioned below, with an aim to address a suitable technology for the proper on-site conversion of solid waste materials generated in non-sewered applications:

1. To provide an overview on the existing solid waste management/stabilisation methods and their associated implementation challenges in commercial/pilot, laboratory and small scales;
2. To select the most promising method and further address the drawbacks.

Nonetheless, the primary aim for these applications is to reduce the waste volumes in sensible amounts and ensure the safe discharge of the products. Typically, the systems implemented for such applications must deal with limitations on regular maintenance and process control for the efficient conversion of sewage-type material in alternative volumes. These additional problems further complicate the design and optimisation of such a system.

Throughout this study, pyrolysis was observed as the most promising method among the existing technologies due to its lower emission rates in large scales and lesser operational challenges both in commercial and small scales. Lower heat fluxes within the reaction area enable the accommodation of alternative feedstocks with lesser necessary optimisation and enhance the handling of moisture content. A major technical challenge observed with this technology is the energy intensity in addition to the pre-treatment (drying), which was addressed through the addition of an on-site rapid energy recovery step from the by-products. A pyrolysis temperature of 400–600 °C and the heating rates pursued at low ranks could result in a sustainable thermal conversion range for moist waste materials. These conditions would aim to produce the maximum yield of syngas with the highest calorific value, which facilitates the combustion performance of the vapour fuel in the afterburner/atomiser. Excessive heat upon the complete combustion of syngas and liquid fuel can potentially limit the energy consumption of pyrolysis or the inevitable drying stage in the system. This study does not take heat waste and ramp up steps into consideration. However, if the overall costs due to energy consumption or pre/post-treatment remain less than the current methods for management or disposal, this solution could be explored through further research. Using a novel design, the detrimental effects of particle size and alternative flow rates on both the conversion efficiency and operational performance could be alleviated through the maximisation of residence times and fuel fluidisation. All of these would aim to produce the highest H₂ and C₁–C₃ fractions in such a range of temperatures while producing an energy-rich gaseous fraction for energy recovery.

For future studies, extensive research on the novel design, useful contents of moisture, potential emissions from such a system and ignition mechanisms of bio-oil in the vapour phase would be suggested.

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**Appendix I - Conference Presentation 2021 - The European
Conference on Fuel and Energy Research and Its Applications,
Nottingham University, 6th – 8th of September**



Chemical process design of solid waste management for use in railway rolling stock

Farhad Beik, PhD researcher in Energy and Power

Supervisors: Dr. Stuart Wagland, Prof. Leon Williams

Sponsor: GBR-Rail Ltd.

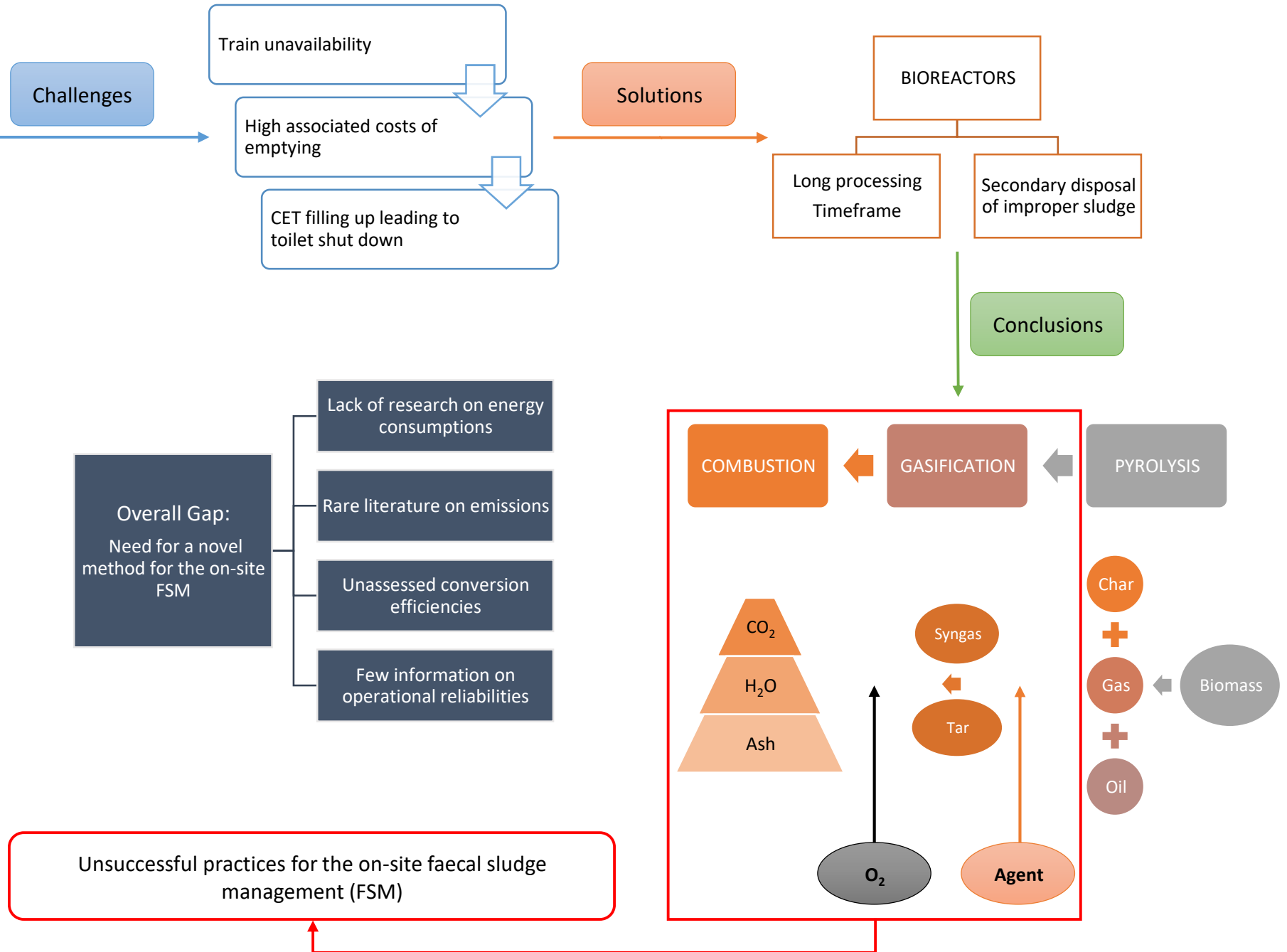
September 8th (2021)

www.cranfield.ac.uk

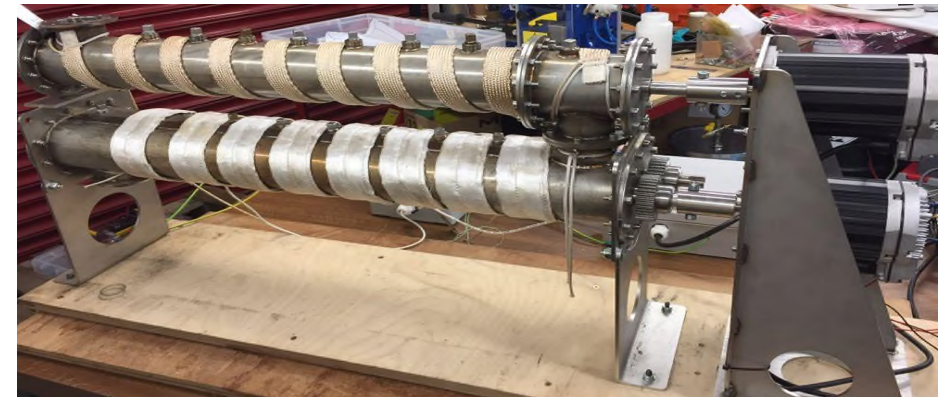
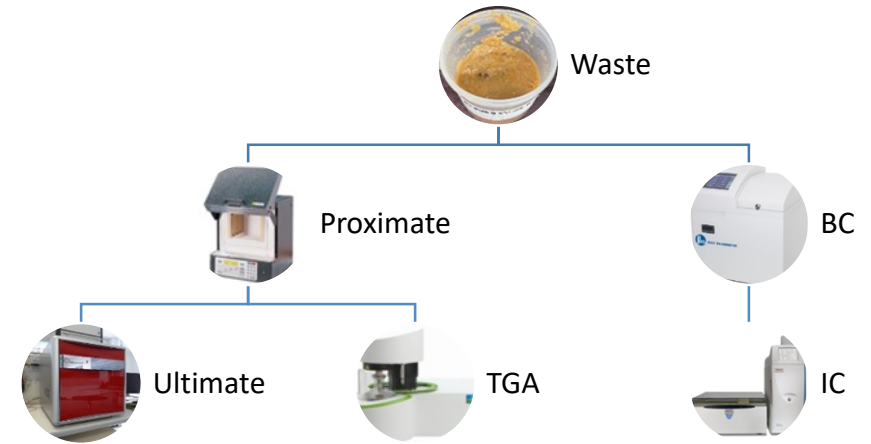
Rolling stock after 1988 have been fitted with CET for managing sewage on trains



❖ Applied research project funded by Garrandale Ltd, looking for the implementation of an on-board wastewater treatment system



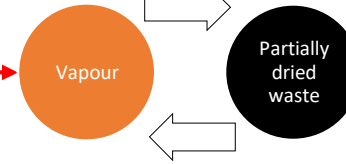
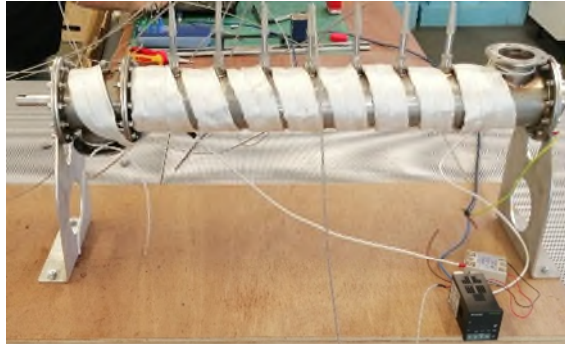
Approach



Overall aim:

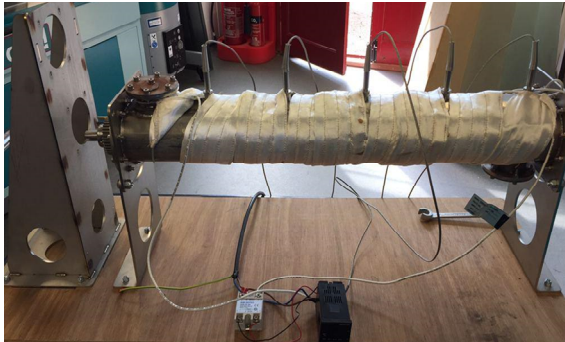
Design and optimisation of a novel pyrolysis system delivering suitable products for rapid combustion and heat recovery as a new method for the on-site faecal sludge management

Approach

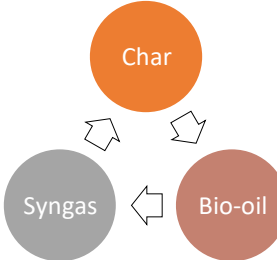


Contributing information on the inorganic extraction through drying

Drying efficiencies and temperature effects on volatile extraction



Partially dried feedstock (30-40-50 and 60 MC%)



Prolonged biomass/gas RT on the yield and composition, contaminant contribution

Contribution of water from initial feedstock and reactions to the bio-oil fractions

Shedding light on the species having impact on the boiling point of the bio-oil (i.e., Saccharides, polyphenols)

Quantification of CO, H₂, CH₄, C₂-C₃ and CO₂

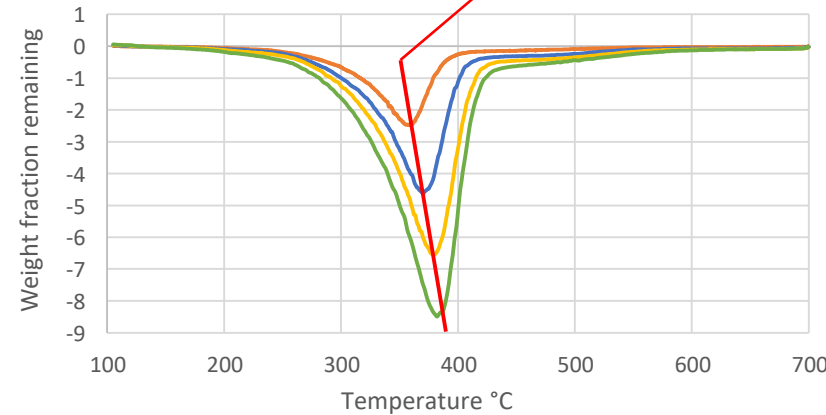
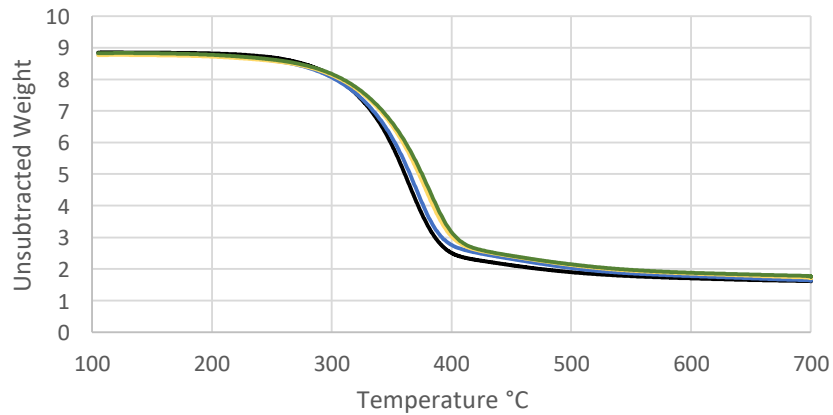
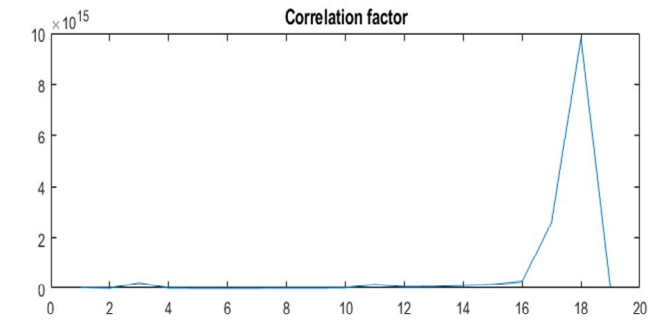
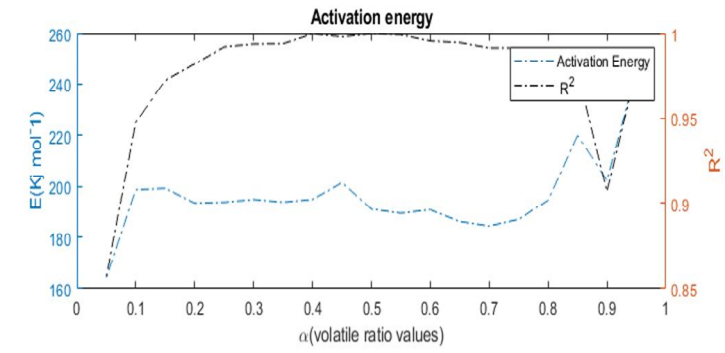
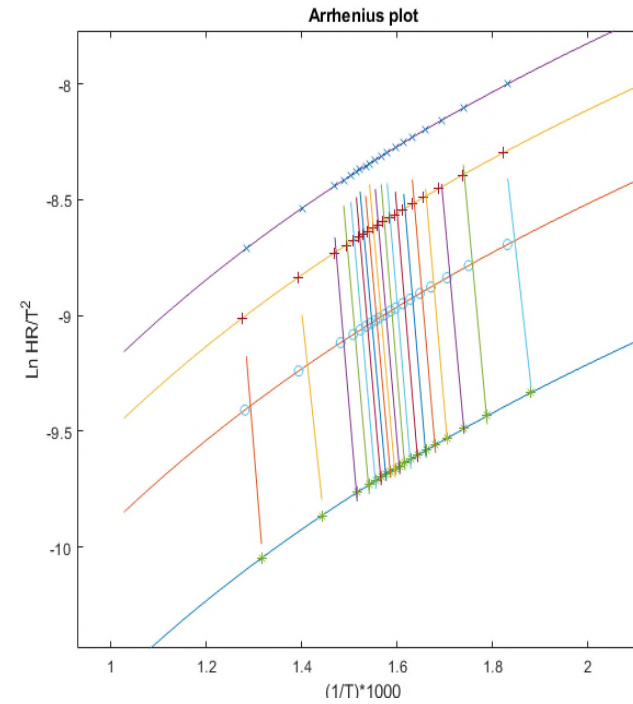
Contributing information on the species leading to the formation of coke (phenol-aldehydes)

Findings

Alternative carbon contents of the waste

Wt.%		Proximate (dry basis %)			Ultimate (dry basis %)				MJ/kg	g/cm ³	
Sample	MC	Ash	V _m	FC	C	H	N	O	CV	S	Cl
1	91	5	82	13	44	7	1	43	18	960	3450
2	90	4	83	13	42	7	1	47	19	--	--
3	93	7	83	10	46	8	2	37	18	--	--
4	92	6	81	13	43	7	1	43	17	--	--
5 (DE)	92	--	--	--	48	7	2	--	--	--	--
TT	6	2	89	9	42	5	0	51	17	--	--

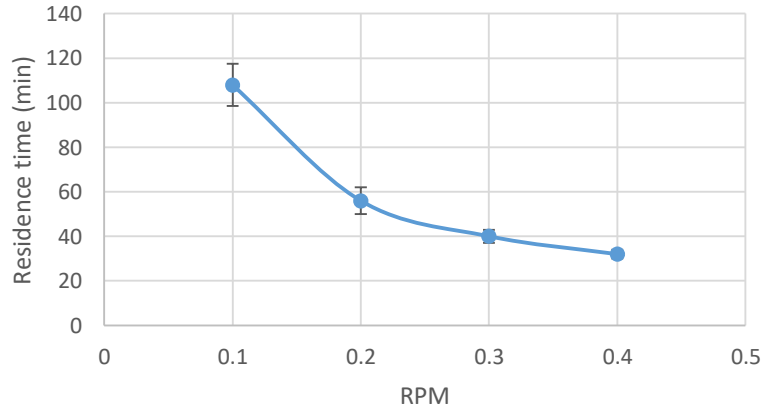
MC% : Moisture content, V_m: Volatile matter, FC: Fixed carbon, DE: Drying experiments, TT: Train tissue, CV: Calorific value



	Activation energy (Kj*mol ⁻¹)	Log ₁₀ (K ₀)
1	153 - 212	9 - 14.5
4	164 - 245	12 - 16
TT	171 - 201	11.5 - 14

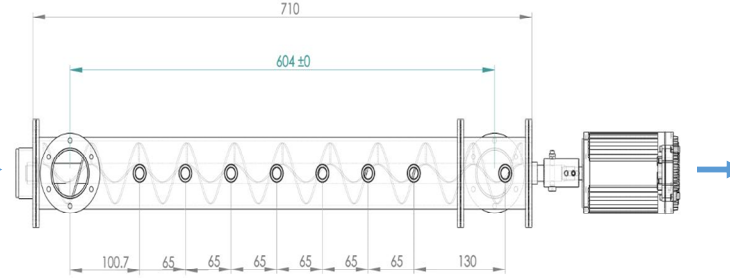
Findings

Achievable residence times in dryer

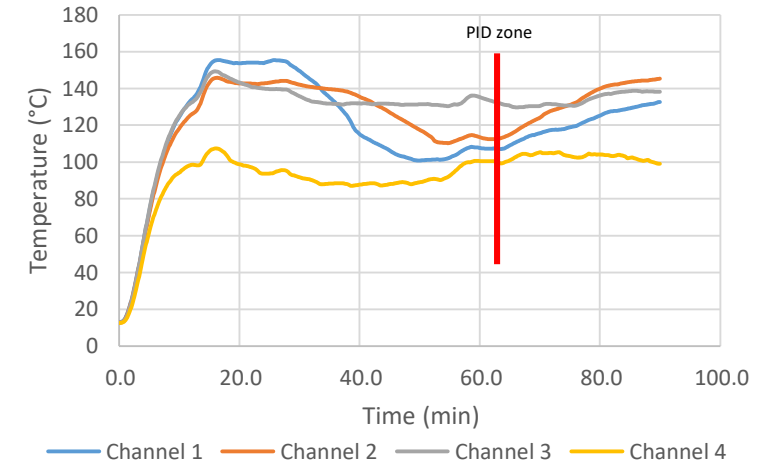


Heating assembly was one heating tape of 1.5Kw

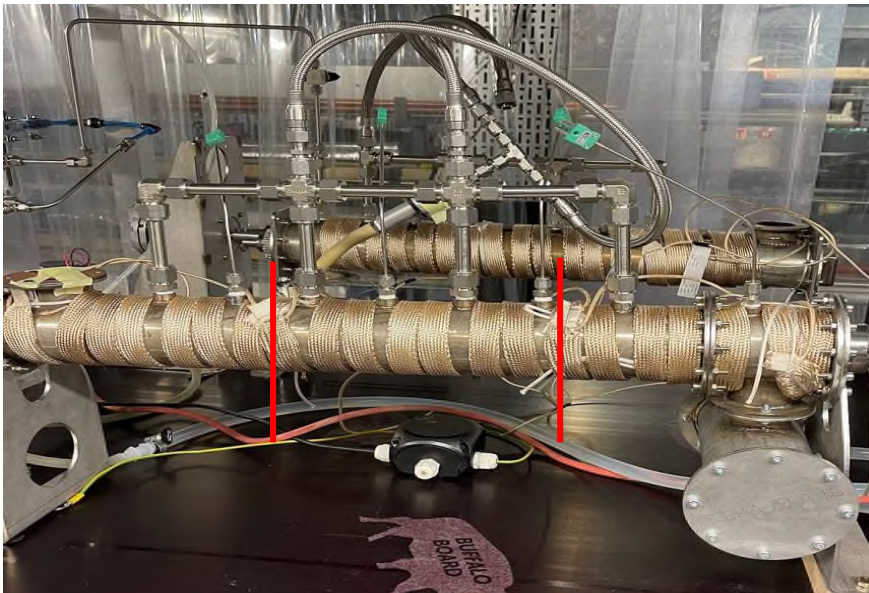
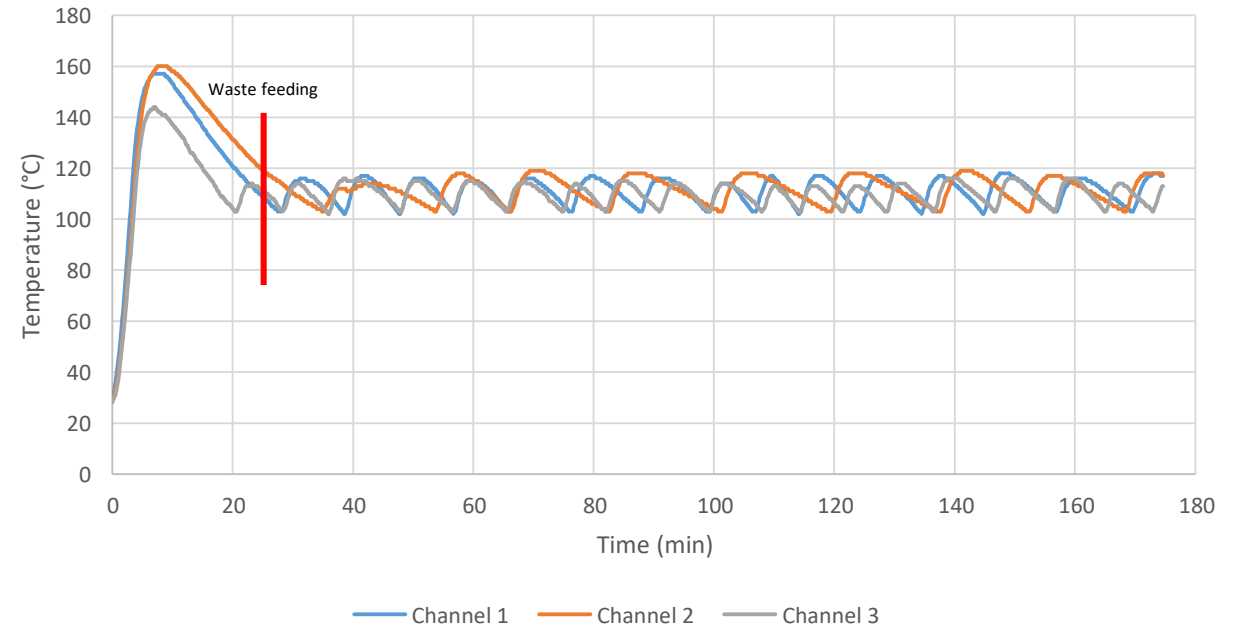
1



Unstable temperature profile

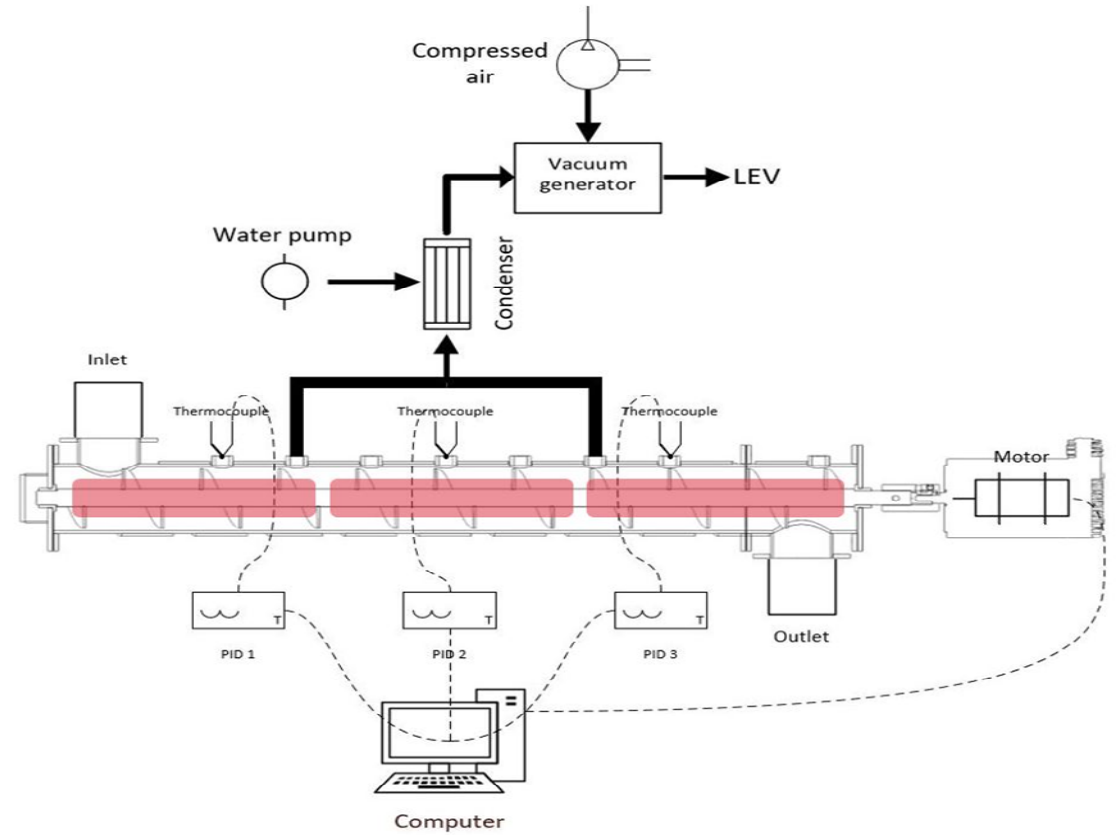
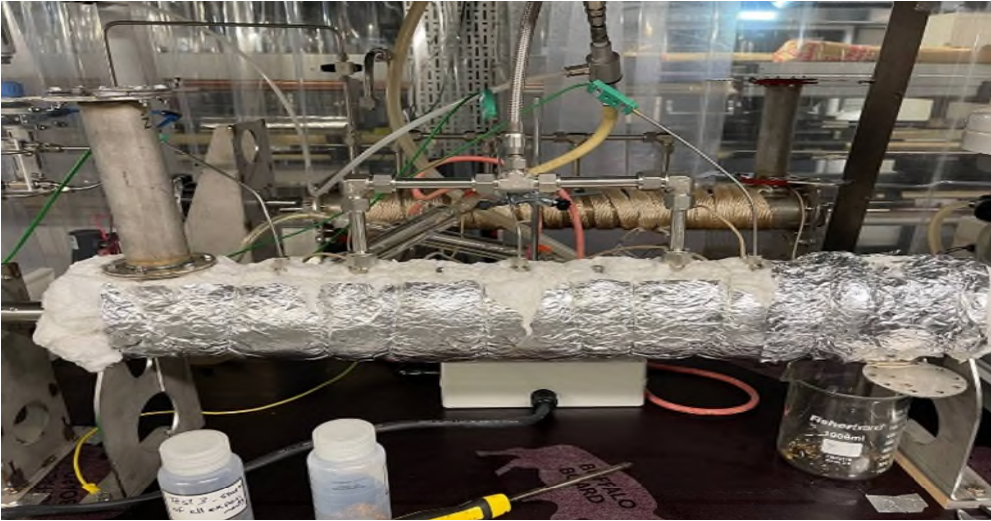


Stable temperature profile

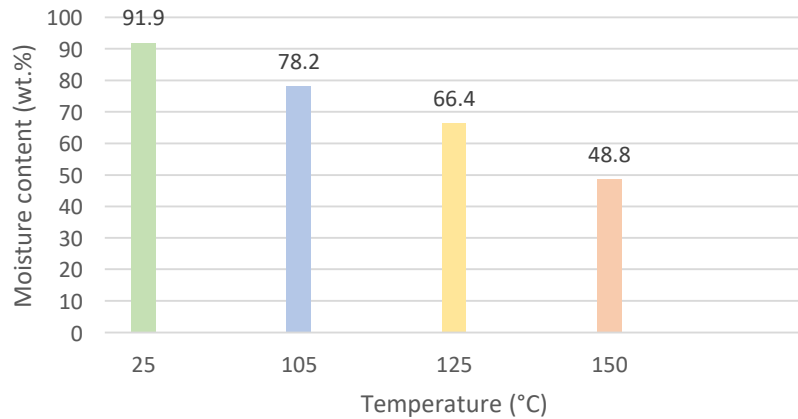


2

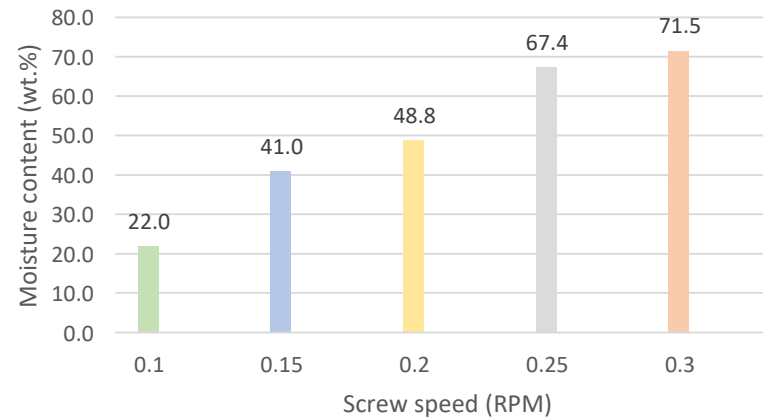
Findings



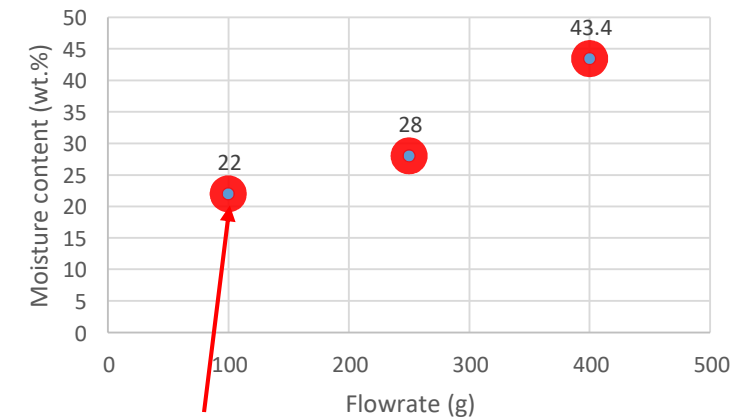
HHT Vs Drying Efficiency/DE (Constant 0.2RPM, 100g)



RPM Vs DE (Constant 150°C, 100g)



Flowrate Vs DE (constant 150°C, 0.1 RPM)

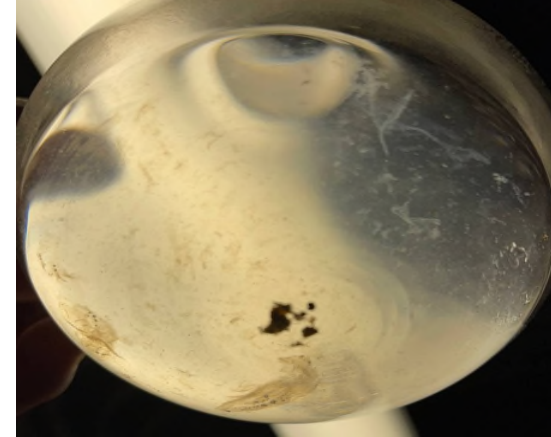


Almost 70% drying efficiency was achieved using 150°C, 2 hours of residence time/0.1 RPM, and 100g feed input (higher heat transfer)

Findings



Waste dried at 150°C and 0.1 RPM



Vapour collected from drying

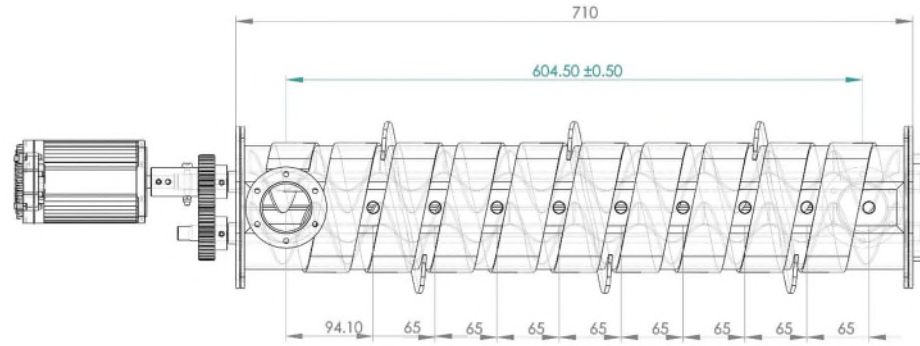
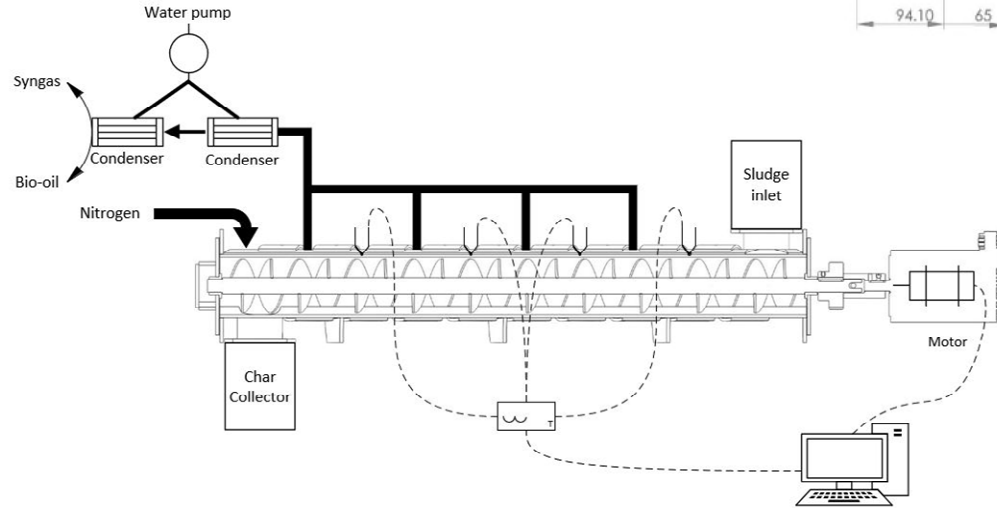
0.2 RPM							150°C							
Temperature							Screw Speed							
Ult%	105		125		150		0.1		0.15		0.2		0.3	
Zone	SU	IN	SU	IN	SU	IN	SU	IN	SU	IN	SU	IN	SU	IN
C	42	41	55	50	43	48	51	45	45	45	43	48	46	48
H	7	6.99	8.58	7.97	7.31	7.45	8.02	7.46	7.20	7.40	7.31	7.45	7.29	7.68

SU: Surface, IN: interior

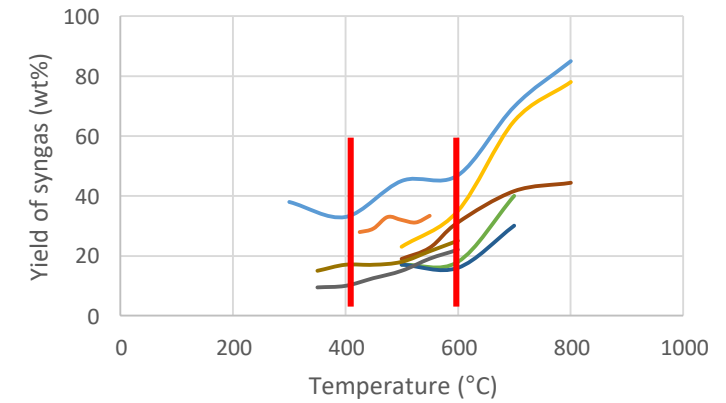
Results from the elemental analysis of the granules prove the negligible carbon emission of the dryer at temperatures of 150°C since in various tests the surface of the granules had more carbon comparing to the interior part of the granules.

Findings

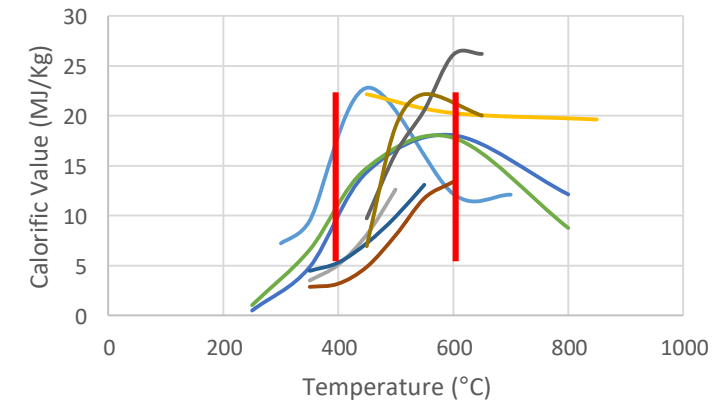
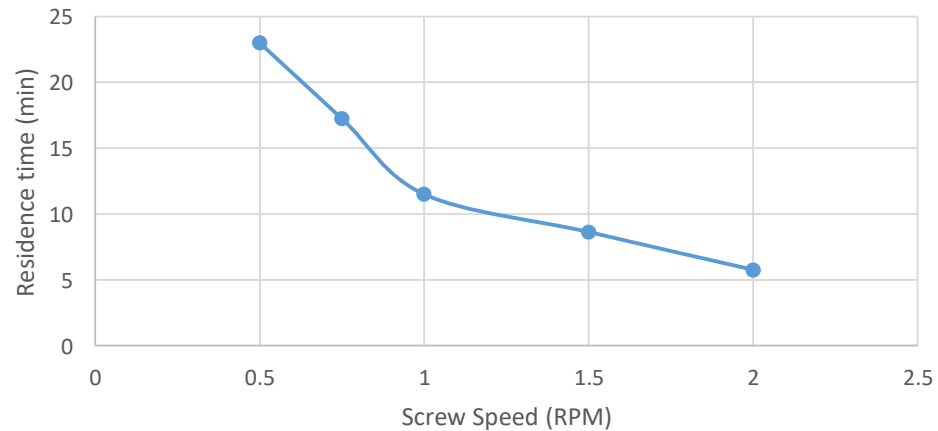
Pyrolysis Unit Schematic



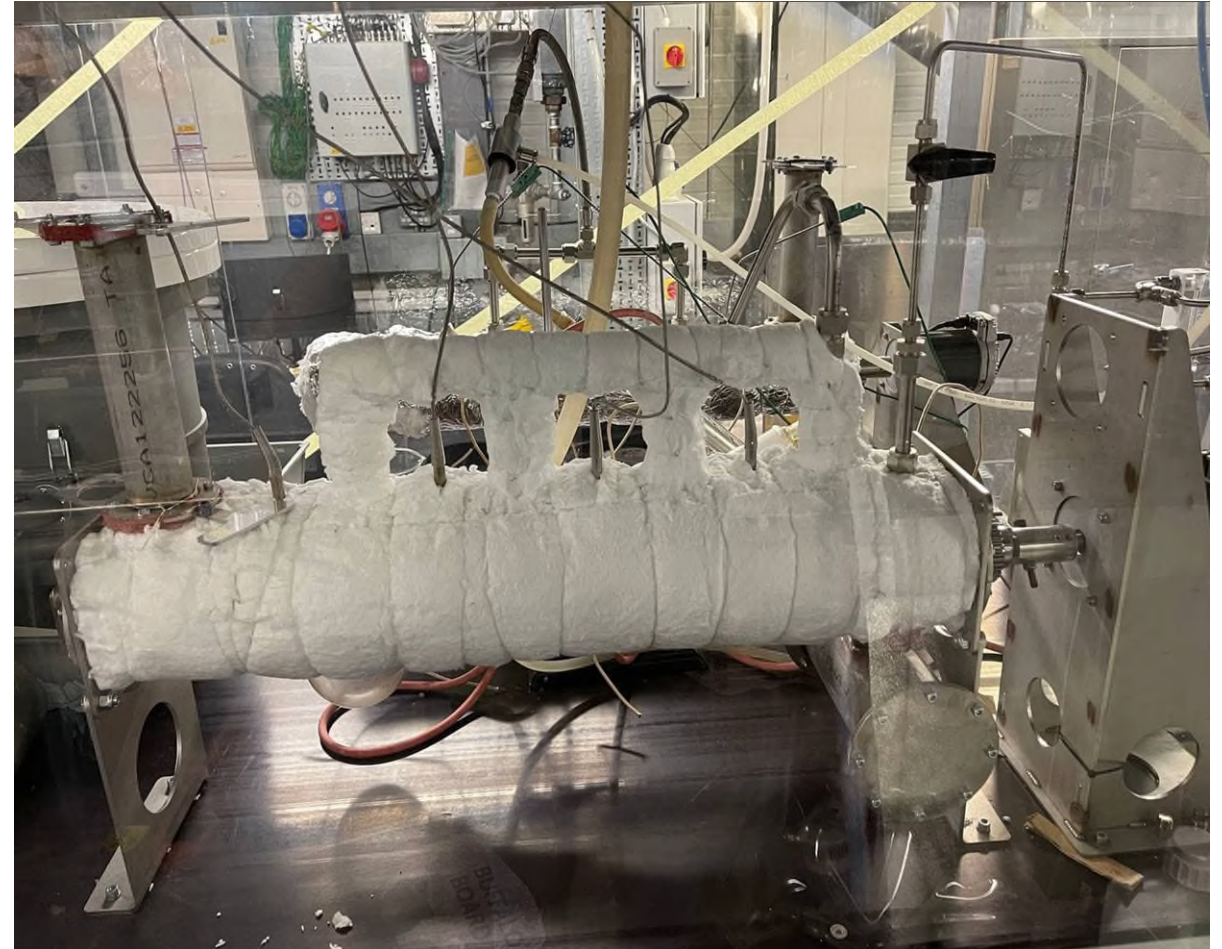
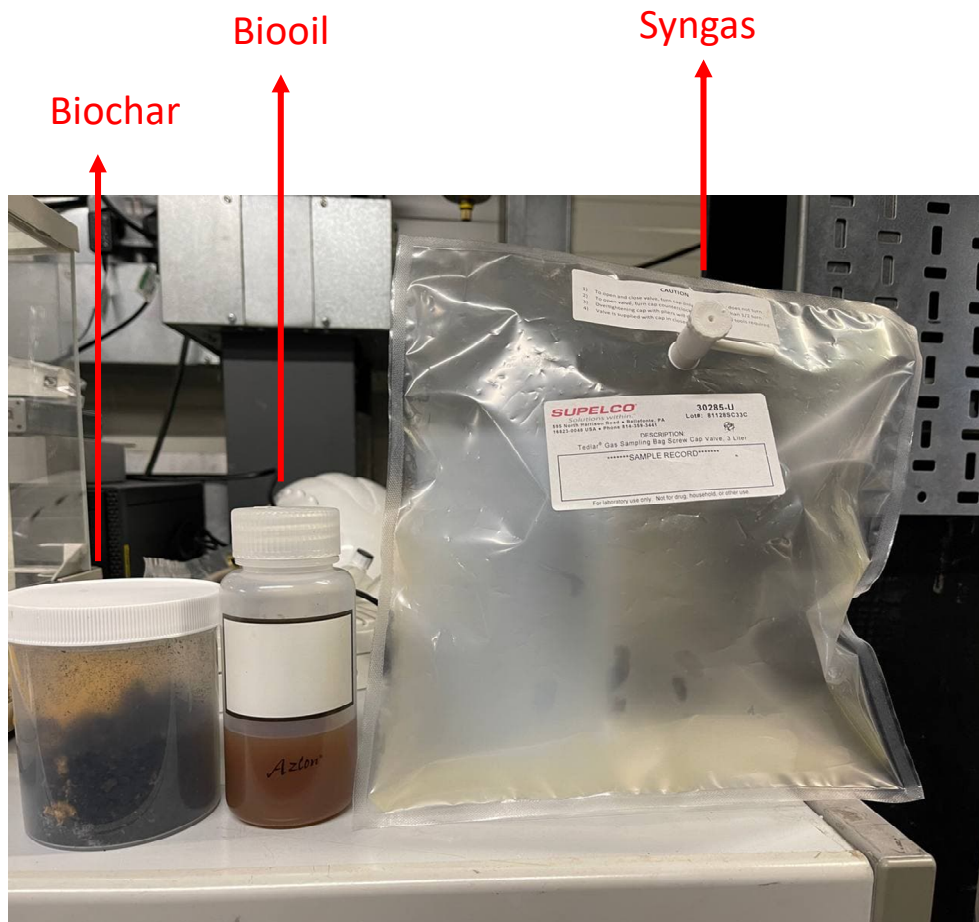
Novelty of literature review: temperature ranges of pyrolysis commissioning lie within 400-600°C



Achievable residence times in pyrolysis reactor



Findings





Conclusion

Contribution to knowledge:

1. Developing a new method for on-site FSM enabling robust operation for complete destruction and disposal of the waste
2. Complete understanding of the moisture content handling in terms of the internal relation in a pyrolysis system implemented for these application
3. Comprehensive contribution to the characteristics and challenges involved with the conversion of such waste materials
4. Providing knowledge on the relation between process parameters and emissions from these specific waste materials never analysed to the best of our knowledge
5. Highlighting the implementation of auger pyrolysis reactors and their efficiencies due to these application's constraints
6. Contribute to a complete industry revolutionizing technology for mobile applications
7. Drying efficiencies of ~70% are achievable while the emissions stay negligible within such dryer.
8. The sizing of such dryer can accommodate the feedstock volumes specified for this application (ranging from 100-400g on various trains)
9. In order to provide a better insight on the emissions, COD of the resultant vapour could be determined. However, no limits/regulations are defined for these applications to the best of our knowledge
10. Extensive research is suggested for future work on the flash point and ignition properties of the bio-oil fraction. This includes the simultaneous combustion with the syngas.



Q&A

Thanks for listening