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Optimisation of the Human Solid Waste Treatment System to
Manage Outputs in Compliance with the ISO 30500

Faculty of Engineering and Applied Science
Centre for Design Engineering and Digital Innovation

MSc by Research
Academic Year: 2024 - 2025

Supervisor: Professor Leon Williams
Associate Supervisor: Dr Serap Ozmen
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This thesis is submitted in partial fulfilment of the requirements for
the degree of MSc by Research in Design Engineering

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Abstract

Nearly half of the world's population is still struggling with inadequate sanitation, especially where sewer systems are lacking. Non-sewered sanitation systems offer a sustainable alternative for human solid waste treatment. This research explores the torrefaction process for treating the solid fraction of human excreta.

The study investigated the impact of torrefaction temperature and retention time on the quality of the solid char and liquid outputs through a series of experiments. Char quality was assessed using proximate and elemental analyses to determine composition, along with pathogen reduction tests for *E. coli* and *C. perfringens*. For the liquid output, chemical analyses were performed, including COD, TSS, TP, TN, and pH analysis.

Results demonstrated that increasing torrefaction temperature from 150°C to 200°C resulted in a reduction of moisture content from 14% to 3% and a decrease in pathogen levels. As the temperature change was relatively small, there was small difference in elemental composition. Treatment at 250°C with 0.083 RPM resulted in a biochar with excellent torrefied properties, including low moisture content (5%), increased hydrophobicity, improved grindability, and nearly full eradication of *E. coli* (<10 MPN/g). A novel rheology chart (RhS-0 to RhS-7) was developed to classify torrefied char based on its progressive transformation, including colour change (light brown, brown to black), increasing hydrophobicity, decreasing moisture and rising fixed carbon levels. This chart addresses a significant research gap by providing a systematic classification of torrefied char, a previously underexplored area. These findings contribute to advancing sustainable waste treatment technologies by providing a decentralised sanitation solution that aligns with ISO 30500 standards.

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Keywords: Human solid waste, Non-sewered sanitation, Torrefaction, Biochar, ISO 30500, Rheology chart.

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List of Abbreviations

VOC	Volatile Organic Compound
SDG	Sustainable Development Goal
RTTC	Reinvent the Toilet Challenge
COD	Chemical Oxygen Demand
TSS	Total Suspended Solids
EC	Electrical Conductivity
TN	Total Nitrogen
TP	Total Phosphorus
TAN	Total Ammonium Nitrogen
BTS	Bristol Stool Chart
CFU	Cell Forming Units
MPN	Most Probable Number
RhS	Rheology State
TOC	Total Organic Carbon
RPM	Rotations per Minute
NSSS	Non-Sewered Sanitation System
EHS	Environment, Health and Safety
FC	Fixed Carbon
VM	Volatile Matter
CO _x	Carbon oxides
NO _x	Nitrogen oxides

1 Introduction

In 2024, nearly half of the world's population- about 3.5 billion people is suffering from a lack of access to safe sanitation facilities (Kone, 2021). Over 1.5 billion people lack even fundamental sanitation services, such as private toilets or latrines, forcing 419 million to practice open defecation in public spaces, behind vegetation, or in natural water sources (World Health Organization, 2024). Additionally, many urban populations use sanitation services, where waste is not safely disposed of and circulates back in their communities (Burwell, 2011). As a result, half a million children under age five perish every year from typhoid, diarrhoea, cholera, and other sanitation-related diseases (Kone, 2021). Limited access to sanitation not only affects people's health but also creates economic difficulties for low-income communities and causes environmental damage (Bill Gates, 2012), resulting in an estimated global cost of \$223 billion annually due to higher health expenses, and declined productivity and wages (Bill Gates, 2018).

Many middle- and low-income countries are urbanising rapidly, thereby increasing the demand for essential services like sanitation. Despite these advancements in these regions, the percentage of the population relying on “underdeveloped” sanitation amenities has increased over the last 23 years (UNICEF, 2018). Most urbanised yet economically challenged populations rely on on-site sanitation (such as pit latrines and septic tanks), which need regular emptying (Tayler, 2018). If not properly treated, this waste is a potential threat to the environment and, in turn, to life as well.

Currently, billions of funds have been invested in repurposing old toilets, sewers, and wastewater treatment systems in these challenged areas. However, traditional sewer-based sanitation designs and solutions dating back over 250 years are not suited for scalable, affordable, and sustainable solutions (Öberg et al., 2020). Furthermore, in many low-income and rapidly urbanising areas, where water is limited, traditional sewer systems pose several challenges. These systems need a large and steady supply of water for waste conveyance and flushing, which can deplete local water resources and infrastructure. As a result, they often become unsustainable and expensive to run and maintain (World

Health Organization, 2018). Additionally, blockages, leaks, and expensive maintenance make them impractical for rapidly growing urban populations in developing nations (Shyu et al., 2021).

Modern sanitation, which relies on large treatment plants, is a potential solution, but these are too costly and complex for developing communities to build and maintain. Therefore, establishing low-cost, scalable innovative technologies that ensure sustainable sanitation for the developing world has become a critical global challenge (Bill Gates, 2012).

Aware of the pressing need, the UN set up SDG 6, which has a target 6.2 to ensure everyone can access sanitation and hygiene by 2030 (United Nations Regional Information Centre., 2025). However, progress remains uneven. The Gates Foundation is leading a \$13.5 million initiative to reinvent toilet technology, which has not significantly evolved in a long time (Georgia Institute of Technology, 2019). In 2011, the foundation started the Reinvent the Toilet Challenge (RTTC) to solve the twin crises of poor sanitation and resource recovery. Its goal is to develop low-cost toilets that sanitise human waste and reclaim valuable resources without relying on sewer connections. As a result, non-sewered sanitation systems (NSSS) have gained global attention and become a key focus area in modern sanitation research and development. The RTTC has catalysed numerous innovative approaches to sanitation, including electrochemical treatment, hydrothermal carbonisation, and supercritical water oxidation (Bill & Melinda Gates Foundation, 2012). These methods deviate from traditional waste management approaches. The challenge has also revealed that answers need to be cutting-edge, cost-effective, and in line with local customs to help the people they're meant for. Yet, a critical issue with these new waste treatment solutions is that they release volatile organic compounds (VOCs), which has led to the search for environmentally sustainable options. In response to these challenges, Cranfield University invented a non-sewered novel toilet system that incorporates torrefaction technology. Torrefaction is a thermal treatment process conducted in an anaerobic environment at relatively low temperature (less than 300°C) (Tumuluru et al., 2011). While other thermal

processes, such as incineration, combustion, pyrolysis, and gasification, can effectively eliminate harmful microorganisms (Samolada & Zabaniotou, 2014), torrefaction is particularly suitable for sustainable sanitation because it operates at lower temperatures, preventing VOC formation while significantly reducing pathogen levels. Additionally, the oxygen-free setting prevents reactions that could create harmful byproducts like CO_x and NO_x (Serio et al., 2016; Yacob et al., 2018). The process is also less energy intensive as it operates at lower temperatures (Tumuluru et al., 2011).

Another advantage of the torrefaction process is the by-product, biochar, which has potential to be used in a range of applications. Torrefaction retains important nutrients like nitrogen (N), phosphorus (P), and potassium (K) in the biochar, along with the organic carbon. These nutrients can improve soil by enhancing its structure, water retention, and microbial activity. Biochar can also be used for odour control in waste management systems and as an adsorbent for removing heavy metals and contaminants from wastewater (Hossain et al., 2020).

The current human solid waste treatment subsystem of the Cranfield NSSS is scaled to satisfy household waste management needs for three to five individuals. This subsystem simultaneously converts human solid waste into pathogen-free biochar, meanwhile utilising the exothermal energy to treat the liquid waste stream generated during the process through an integrated liquid management unit. This system aims to comply with ISO 30500, an international standard for non-sewered sanitation systems to ensure the safety and effectiveness of this system.

ISO 30500 specifies that system outputs must meet human health and environmental safety criteria before being reused or disposed of. Human faeces contain approximately 10¹⁰ microorganisms per gram of dry matter, including harmful pathogens such as bacteria (*Escherichia coli*, *Salmonella*), viruses, and parasites that can cause serious diseases if not properly managed (Schönning et al., 2007, Niwagaba et al., 2006). While this research aims to produce pristine biochar from human faecal matter, incomplete torrefaction may result in partially treated biochar. This partially treated biochar poses an environment, health and

safety (EHS) risk by improper disposal, potentially leading to soil deterioration and reduced agricultural production (Xiang et al., 2021). To ensure environmental safety quality standards, this study systematically evaluated the chemical and microbiological characterisation of the treatment unit's outputs.

To break through these challenges, the present study aims to optimise the torrefaction process and thus improve the treatment of human solid waste. Given the highly variable composition of human faecal matter, the identification of optimal operating conditions remains a challenge. The Bristol Stool Chart (BTS) is utilised to describe the consistency of faeces, enabling the understanding of input variability and how it impacts the torrefaction process (Lewis & Heaton, 1997). The study systematically investigates the inter-relationship of waste composition and corresponding operating conditions for torrefaction, such as temperature, residence time, and feedstock characteristics, to develop an efficient and reliable treatment system. Through the optimisation of these parameters, the study aims to produce high-quality biochar while satisfying ISO 30500 standards. Ultimately, this research will contribute to the development of a standardised, non-sewered sanitation system that is safe, effective, and sustainable. Furthermore, this study supports the creation of a circular economy through the transformation of waste into a valuable product, reducing environmental risks, and providing an alternative to traditional sewer-based sanitation, particularly in low-income and fast-urbanising areas.

1.1 Research Gap

Significant progress has been made toward optimising the torrefaction process for waste treatments, but several key gaps remain in the literature. The most significant innovation gap identified in this research is the absence of a comprehensive char-rheology chart for torrefied human solid waste, which currently does not exist in the research field. This innovation is particularly crucial given that human solid waste varies considerably in composition, making it challenging to maintain consistent input parameters during testing and analysis. However, by focusing on output characteristics rather than input standardisation, it is possible to establish a framework that will be valuable for future research and

applications. The proposed char rheology chart will define various rheological states and their associated chemical, physical and biological properties, providing a standardised reference for researchers. While extensive research exists on biomass torrefaction for energy applications, the unique challenges posed by human waste – including pathogen elimination and nutrient recovery – require specific investigation. The development of a comprehensive char rheology chart will address this gap by incorporating *E. coli* and *C. perfringens* levels at each rheology state, along with elementary analysis data. This approach represents a paradigm shift from traditional input-focused methodologies and addresses the fundamental challenge of feedstock variability in human waste torrefaction systems.

Furthermore, most research in this area has focused mainly on feedstock types such as agricultural residues and energy crops; there are only limited studies on human waste. The statement is supported by Ilango & Lefebvre, (2016), who highlight that pyrolysis research has predominantly focused on plant-based materials due to the widespread availability of cellulosic biomass. Their study further emphasizes that the hazardous and noxious nature of faecal matter presents challenges for its thermal processing, making the pyrolysis of human waste even less common and largely confined to municipal sludge treatment. Torrefaction of human solid waste presents some of the most interesting opportunities as its unique chemical compositions differ from traditional biomass sources. Additional research is needed to optimise torrefaction for human solid waste, especially on how parameters such as temperature and torrefaction time will impact the process performance. This would offer valuable insight for optimisation to improve efficiency and sustainability.

Another critical research gap involves managing the torrefaction outputs. In most studies, the primary focus is on solid char. Liquid and gas by-products of torrefaction have received far less attention, despite their potential to enhance the sustainability and economic viability of the process. Effective management strategies for capturing and utilising these by-products could lead to valuable secondary products or alternative energy sources. While some studies highlight

benefits such as reduced greenhouse gas emissions, further research is needed to assess their full environmental and socio-economic impacts (Yacob et al., 2018). A deeper understanding of these aspects will help optimise torrefaction systems for both efficiency and sustainability. Addressing these gaps is essential for developing scalable, cost-effective, and environmentally sustainable sanitation solutions.

1.2 Aim and Objectives

This research aims to optimise the human solid waste treatment system by managing uncontrolled solid inputs and producing quality outputs in compliance with ISO 30500 standards. To achieve this, the following objectives have been established:

- Conduct a literature review by studying recent research on torrefaction, exploring methods for non-sewered systems, and understanding the requirements of ISO 30500 standards.
- Develop a research methodology by designing test plans aligned with ISO 30500, with a particular emphasis on analysing the chemical, mechanical, and biological properties of the char.
- Gather data through testing by conducting controlled experiments over 5 months to examine torrefaction and pathogen elimination while collecting data on the physical, chemical, and biological characteristics of char output.
- Analyse and reflect on the results by creating a char rheology chart and providing insights into the safe treatment of human waste with minimal VOC emissions while producing pathogen-free biochar.

2 Literature Review

This chapter covers key aspects of human solid waste and its treatment technologies, with a focus on torrefaction as a sustainable solution. It begins with an overview of human solid waste, including its composition and characteristics, followed by a discussion of various treatment technologies, highlighting their advantages and limitations. The torrefaction process is explored in detail, examining its mechanisms and suitability for waste treatment. Additionally, the properties of torrefied biomass are analysed, emphasizing improvements in fuel quality, pathogen reduction, and waste manageability. The chapter also discusses regulatory frameworks, particularly ISO 30500, which set standards for non-sewered sanitation systems. By synthesizing existing research, this review identifies knowledge gaps and lays the foundation for advancements in sustainable human waste management.

2.1 Human Solid Waste

2.1.1 Human Solid Waste Characterisation

Human faecal waste is semi-solid blend of fresh, undigested or partially digested excreta, along with associated cleansing agents and tissues. It is highly variable in characteristics and consistency depending on a person's health and diet. Mainly, it is made of macromolecular organics (carbohydrates, protein, fats) 84–93%, fibre, inorganic materials 7–16% and pathogenic microorganisms (Penn et al., 2018).

The moisture content of human faeces ranges from 63% to 86% w/w. The pH of faeces varies between 5.3 and 7.5, while the chemical oxygen demand (COD) ranges from 20,000 to 50,000 mg/L (Rose et al., 2015). Untreated human faeces are hazardous due to the possible presence of harmful bacteria, viruses, parasitic organisms, and intestinal worms (Rose et al., 2015). Previous research reported that live and dead bacteria comprise between 25% and 54% of the dry weight of faeces (O'Hara A, 2018).

The “Bristol Stool Form Scale” introduced by Lewis and Heaton (1997) shows the high variability of faeces physical structure. Fresh human solid waste is typically brown and tends towards dark brown. The scale divides stools into seven categories, from type 1 (dry, hard lumps) to type 7 (watery stool). Types 3 and 4, referred to as "solid, lumpy log" and "soft, smooth coil," are considered normal stool types. This is used to characterise the texture, forms and variation of human faeces based on visual appearance (Afolabi & Sohail, 2017).

The median faecal wet mass is reported as 128 g per person per day, based on data from 116 studies on healthy individuals. However, values vary widely, ranging from a minimum of 51 g to a maximum of 796 g per person per day (Rose et al., 2015). Key factors influencing faecal generation rates include total food intake, body weight, and diet (Rose et al., 2015). Additionally, ISO 30500 confirms that the average faecal production rate is approximately 250–350 g per person per day, with 250 g per person per day observed in urban low-income settings and 350 g per person per day in rural low-income settings (BS ISO 30500, 2018).

2.2 Human Solid Waste Treatment Technologies

There are several approaches to generating biochar from biomass, which are primarily categorized into biological, thermal, and thermochemical processes.

2.2.1 Biological Conversion

There are different biological treatment methods for faeces, such as anaerobic digestion, aerobic composting, vermicomposting, and black soldier fly larvae treatment.

2.2.1.1 Anaerobic Digestion

Anaerobic digestion is the microbial breakdown of organic compounds into biogas in an oxygen-deprived setting. The process duration varies from 7 days to 5 weeks, with an organic material conversion efficiency of 30-60% (Oladejo et al., 2019). This process is low-cost and produces simple, useful by-products like methane for energy recovery and stabilised sludge for fertiliser. Furthermore, it

enables the usage of organic feedstock with high moisture content without reducing biogas energy output (Beik et al., 2021).

Anaerobic digestion does not directly produce biochar. Instead, the biomass is converted into sludge, which can then be further processed into biochar through thermal processes (Biochar Today, 2024). This process takes a long time to complete and only converts a portion of the organic materials, resulting in low energy recovery. It is also ineffective in removing dangerous components from sludge and results in a small reduction in sludge volume (Beik et al., 2021).

2.2.2 Thermal Conversion

Thermal treatment approaches have proved to be appealing for resource and energy recovery, treatment, and disposal of sewage sludge (Beik et al., 2021).

2.2.2.1 Conventional Combustion

Combustion occurs at high temperatures (800–1150°C) with surplus oxygen, ensuring complete oxidation of organic matter and converting carbonaceous materials into flue gases while generating heat. Through combustion, sludge volume decreases by up to 90%, and the resulting ash can be used to form construction materials (Beik et al., 2021). Complete pathogen removal and sterilization can be achieved through combustion, with the potential for energy recovery. It is widely used for medical and municipal waste treatment (Han et al., 2012). Multiple hearth furnaces and fluidized bed furnaces are the common reactors used for combustion (Han et al., 2012). The process faces obstacles from high nitrogen oxides and sulphur oxides emissions along with contamination from heavy metals and inefficiencies in heat production caused by inorganic substances. Ignition with auxiliary fuel induces combustion which demands both pre-treatment of the fuel and reduction of its moisture content. The system requires comprehensive measures to control emissions from pollutants. The operation faces challenges such as ash and particulate management along with controlling extreme heat fluxes inside the reaction area (Beik et al., 2021).

2.2.3 Thermochemical Conversion

2.2.3.1 Pyrolysis

Pyrolysis is the thermal degradation of carbon-based materials, under an inert gas at 350–900 °C (Beik et al., 2021). In this process, depolymerization, fragmentation, and cross-linking of lignocellulosic components such as cellulose, hemicellulose, and lignin take place, yielding liquid pyrolytic oil (condensable volatiles), pyrolysis gas (non-condensable volatiles), and char (solid residue) (Samolada & Zabaniotou, 2014; Yaashikaa et al., 2020). The gases produced include methane, carbon dioxide, hydrogen, and synthetic gas (C1–C2 hydrocarbons). The yield of biochar is dependent on the type of biomass and on the temperature used in the process. To illustrate, increasing pyrolysis temperatures lead to lower biochar yields and higher syngas generation (Wei et al., 2019). Pyrolysis can be classified into three types based on the heating rate and residence time: slow pyrolysis, rapid pyrolysis, and flash pyrolysis (Jahirul et al., 2012). Pyrolysis has various advantages, including operating with no need for auxiliary fuel since it works in an oxygen-free environment, as well as pathogen removal and sterilization. Moreover, this technology releases lower emissions compared to combustion and gasification, and it is less sensitive to the feedstock's physical properties (Beik et al., 2021). Pyrolysis ultimately preserves inorganic and metal-rich fractions in the char fraction and works at lower heat fluxes and in low-heating systems, leading to stable reactor performance and a potential way to recover energy from their products. Nevertheless, there are also drawbacks, including the need for pre-treatment of the feedstock (drying and/or heat treatment), the energy-intensive process itself, and limited applicability on a larger scale (Beik et al., 2021).

2.2.3.2 Hydrothermal carbonization

Hydrothermal carbonization converts biomass to biochar at low temperatures (180–250°C), favouring its economic feasibility (Lee et al., 2018). The resulting product is referred to as hydrochar, which differs from biochar obtained via dry processes (e.g. pyrolysis, gasification) (Lee et al., 2018). In this process, biomass is mixed with water and placed in a sealed reactor, where the temperature is

gradually increased to ensure stability. Depending on the operating temperature, different products can be produced: biochar at temperatures under 250°C through hydrothermal carbonization, bio-oil between 250–400°C via hydrothermal liquefaction, and gaseous products (syngas: CO, CO₂, H₂, and CH₄) at temperatures above 400°C through hydrothermal gasification (Yaashikaa et al., 2020). Hydrolyzed biomass can also be transformed into intermediate compounds through sequence processes like dehydration, fragmentation, and isomerization. These intermediates undergo successive condensation, polymerization, and intramolecular dehydration to result in hydrochar (Bakraoui et al., 2020).

2.2.3.3 Gasification

Gasification is a thermochemical process that involves the partial oxidation of a material, typically in the presence of limited oxygen. It decomposes carbonaceous materials into gaseous products in the presence of gasification agents (Defra, 2013). This process takes place over a temperature range of 700-1000°C. Gasification produces syngas as the main product such as H₂ and CO, and other gases, such as CO₂ and CH₄. It generates char as a by-product in lesser amounts (Beik et al., 2021). The reaction temperature is a key factor affecting syngas production, with higher temperatures leading to increased production of carbon monoxide and hydrogen, while reducing the generation of methane, carbon dioxide, and other hydrocarbons (Prabakar et al., 2018). Gasification can be beneficial for various reasons, for instance, it is highly efficient when it comes to recovering energy and helps reduce environmental emissions since it yields a “cleaner” syngas. This process achieves a high degree of volume reduction of the feedstock as well as the complete inactivation and sterilisation of any pathogens. A disadvantage of gasification is that it requires feedstock drying, which can raise the energy requirement. It also requires ignition with other fuel to initiate the process. In addition, large-scale gasification processes are still being developed, and value chains will take time to materialise. Finally, the implementation of this technology can be limited by the requirement for a gasifying agent, like oxygen, air or steam (Beik et al., 2021).

2.3 Torrefaction Process for Biomass and Waste Treatment

Torrefaction, a thermal conversion technology that has gained significant attention in recent years, is a thermochemical process involving the interaction of drying and incomplete pyrolysis. It's an endothermic process involving slow heating of biomass between 200 °C and 300 °C in a controlled atmosphere without oxygen (Jiang et al., 2024). In the torrefaction process, solid waste is transformed into valuable, pathogen-free char with reduced moisture content and increased energy density compared (Tumuluru et al., 2011). Moreover, a small quantity of liquid and non-condensable gas is generated (Durak, 2023).

The torrefaction process is affected by several parameters, including reaction temperature, heating rate, absence of oxygen, ambient pressure, flexible feedstock, feedstock moisture, and feedstock particle size (Tumuluru et al., 2011).

Torrefied biomass has approximately 30% more energy density than original biomass. As torrefaction temperature and time increase, solid yield decreases but volatile yields increase (Niu et al., 2019). W. H. Chen et al., (2019) conducted a TGA analysis to examine the torrefaction of hemicellulose, cellulose, and lignin across a temperature range of 230°C to 290°C. The results indicated that hemicellulose underwent significant degradation even at 230°C. Cellulose, however, was only noticeably affected at temperatures as high as 290°C. Lignin remained relatively unaffected throughout the entire temperature spectrum (Niu et al., 2019).

Although there are several other methods for the treatment of solid waste, which includes combustion, hydrothermal carbonization, supercritical oxidation, and pasteurization, torrefaction offers unique advantages. It operates at moderately low temperatures, requiring less energy input (Mamvura & Danha, 2020). In addition, torrefaction technologies can reduce greenhouse gas emissions, aligning with Sustainable Development Goals (SDGs) (Yacob et al., 2018).

During torrefaction, biomass partly decomposes, giving off various types of volatiles. About 70% of the mass is retained as the torrefied biomass while 30%

escapes as volatile gases and vapours (Mamvura & Danha, 2020). The volatile gases produced can be directed through a condenser, where various liquid products, including water, organic compounds, and lipids, are formed (Tumuluru et al., 2011). The gases produced are predominantly composed of carbon monoxide (CO), carbon dioxide (CO₂), minor amounts of methane (CH₄), light hydrocarbons (C_xH_y), and residual hydrogen (H₂), oxygen (O₂), and nitrogen (N₂) (Mamvura & Danha, 2020).

Initially, torrefaction research focused on its fundamental principles and on the impact on biomass properties on performance (D. Chen et al., n.d.; Kangas et al., 2014; Lestander et al., 2014). Following research shifted towards improving the energy content and fuel properties of biomass (Felfli et al., 2005; Nimlos et al., 2003; Reed et al., 2002). Several studies have been conducted to determine how torrefaction significantly alters the physical and chemical characteristics of biomass, enhancing its combustion performance and energy application potential (Kambo & Dutta, 2014; Wen et al., 2014). Also, research focused on a wider range of feedstocks, including crop by-products, bioenergy plants, and discarded materials, to evaluate torrefaction performance and its suitability for various applications (Mpungu et al., 2024; Negi et al., 2020).

More recent advancements have aimed to enhance the technology's energy efficiency, reduce environmental impact, and improve process control. Studies have highlighted that torrefaction offers environmental benefits, including reduced greenhouse gas emissions (Cahyanti et al., 2020). New technologies focus on capturing and utilizing volatile gases produced during torrefaction (Yacob et al., 2018). Environmental concerns have led researchers to explore efficient uses for the char produced during torrefaction, such as in soil amendments or industrial applications (Safaei et al., 2016).

Currently, torrefaction technologies utilize reactor designs created for processes such as drying, pyrolysis, or gasification. These reactors are adopted and modified for the torrefaction process. Reactor types are selected based on the movement of the feedstock, the method of heat transfer, and the type of media used. Commercially developed or lab-scale reactors include fixed-bed reactors,

rotary drum reactors, screw reactors, microwave reactors, and moving-bed reactors (W. H. Chen et al., 2021). To provide heat for the torrefaction process, innovative heating technologies have been employed, including electric resistance heating (D. Chen et al., 2022).

In 2024 December, a search for the terms "torrefaction" and "biomass" in article titles from the past five years revealed a growing interest in this area. This query search on scientific literature search engines yielded different figures, with "Scopus" selecting 2604 studies, "Science Direct" showing 5611 results, and "Google Scholar" yielding more than 28300 studies. The main countries conducting research in this area were China, the United States, and Malaysia, with China having the highest number of publications.

2.4 Physical Properties of Solid Torrefied Biomass

Torrefaction of biomass significantly changes its physical properties like moisture content, density, grindability, palatability, hydrophobicity, and calorific value, and its chemical composition in terms of carbon, hydrogen, oxygen, nitrogen, and sulphur (Sadaka & Negi, 2009).

With increased temperatures and residence time, the solid yield decreases, while the volatile yields and energy density increase. As the torrefaction temperature increases, the carbon content in the biomass rises, while the levels of hydrogen and oxygen decrease. This is attributed to the release of volatile compounds, such as water and CO₂ (Niu et al., 2019).

It is well-established that torrefied biomass tends to be browner than the parent biomass. As the torrefaction temperature increases, the biomass undergoes structural changes, including the breakdown of filaments, leading to a brittle texture. This brittleness also improves its grindability, resulting in a smaller particle size distribution (Ivanovski et al., 2023).

The hydrophobicity of biomass is closely linked to the contents of hemicellulose, cellulose, and lignin. During torrefaction, hemicellulose, which has a high-water sorption capacity, is degraded, which decreases water uptake by the biomass. This leads to enhanced hydrophobicity, making torrefied biomass more suitable

for long-term storage without the risk of biological degradation. Higher torrefaction temperatures generally result in biomass with higher hydrophobicity, as moisture absorption decreases (Tumuluru et al., 2011).

Torrefied biomass is a high-quality fuel that works better than unprocessed feedstocks in stoves and gasifiers, improving the calorific value and thermal energy of these systems (Boersma & Kiel, 2005).. It can also be used as a premium smokeless fuel for industrial, commercial, and domestic purposes or as a feedstock for fuel pellets, briquettes, and cofiring with coal in power plants (Boersma & Kiel, 2005).

2.5 ISO 30500 and Regulatory Standards for Non-Sewered Sanitation

Several standards and guidelines are available to guide the design, implementation, and operation of non-sewered sanitation systems. ISO 31800:2020, guidelines for faecal sludge treatment units, has published guidance for the effective and sustainable use of integrated treatment units in non-sewered sanitation systems (ISO PC 318, 2024). The WHO (2018) Guidelines on Sanitation and Health offer critical insights into public health considerations for sanitation, emphasizing the importance of safe, hygienic practices in sanitation systems (Guidelines on Sanitation and Health, 2018), while EN 12566 (2000-2020) is a European reference standard for small wastewater treatment systems (BSI - BS EN 12566-1, 2025). These standards work together to ensure that non-sewered sanitation systems operate effectively and in compliance with health, environmental, and regulatory standards.

This research considers the BS ISO 30500:2018 standard (BS ISO 30500, 2018), designed for non-sewered sanitation systems, to ensure that the system meets safety and quality standards globally. ISO 30500 was issued in 2018 to lay down specifications regarding the performance, safety, reliability, and maintainability of NSSS, focusing on sustainable and hygienic sanitation solutions. The system used in this research is part of a developing NSSS, which is why this standard is followed instead of others. The final product will meet ISO 30500 criteria. To achieve this, subsystem-level testing is being conducted while adhering to the

standard. To evaluate the efficiency of the treatment process, key parameters such as total nitrogen (TN) and phosphorus (TP), pH, chemical oxygen demand, and total suspended solids are analysed for the effluents. For the solid output, the analyses targeted human enteric bacterial pathogens, especially *Escherichia coli*, and focused on human enteric protozoa, considering *Clostridium perfringens* as the surrogate indicator. This would ensure that the system will provide high standards according to ISO 30500 concerning public health and the environment.

3 Methodology

This chapter comprised of the sample collection process, the experimental setup, and the pilot tests conducted to characterise the system performance. It also covered how the system has evolved based on pilot tests, modifications made, challenges encountered, and final improvements. Additionally, the chapter illustrated the five-day continuous testing, performed to evaluate the system performance, and the optimisation process to determine the best operating conditions. The chapter further detailed the tests performed to analyse the outputs, as per ISO 30500 guidelines. Finally, it discussed the development of a novel char rheology chart based on char outputs collected throughout the testing period.

3.1 Experimental Set Up and System Design

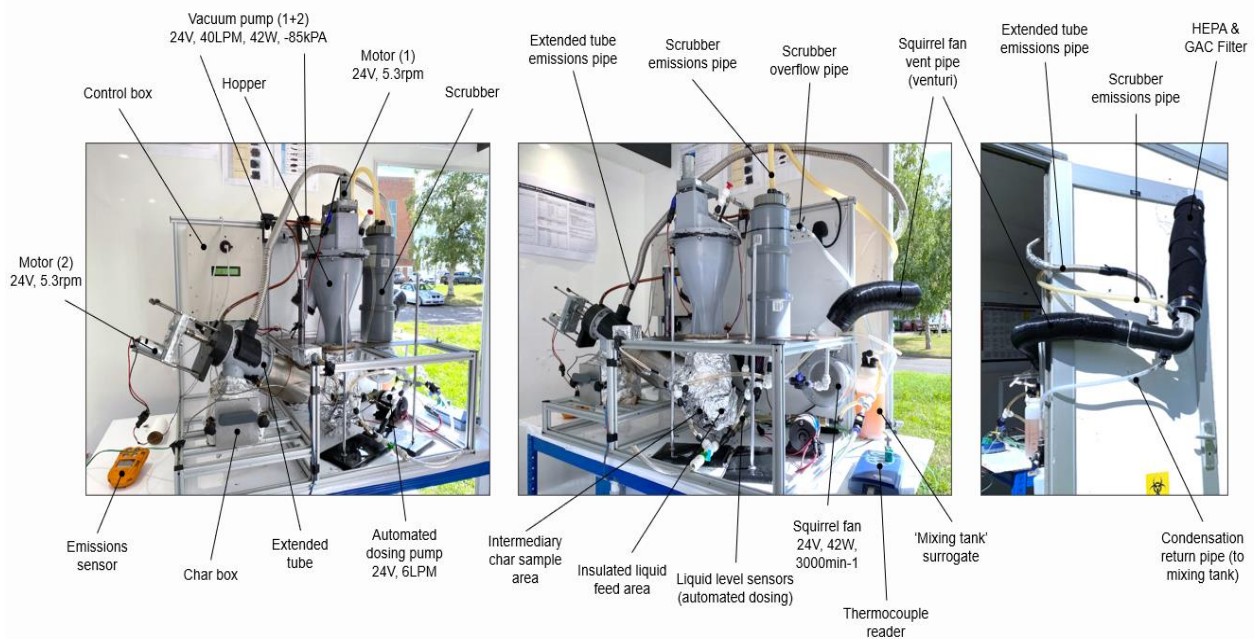


Figure 3-1 Human solid waste treatment subsystem set-up

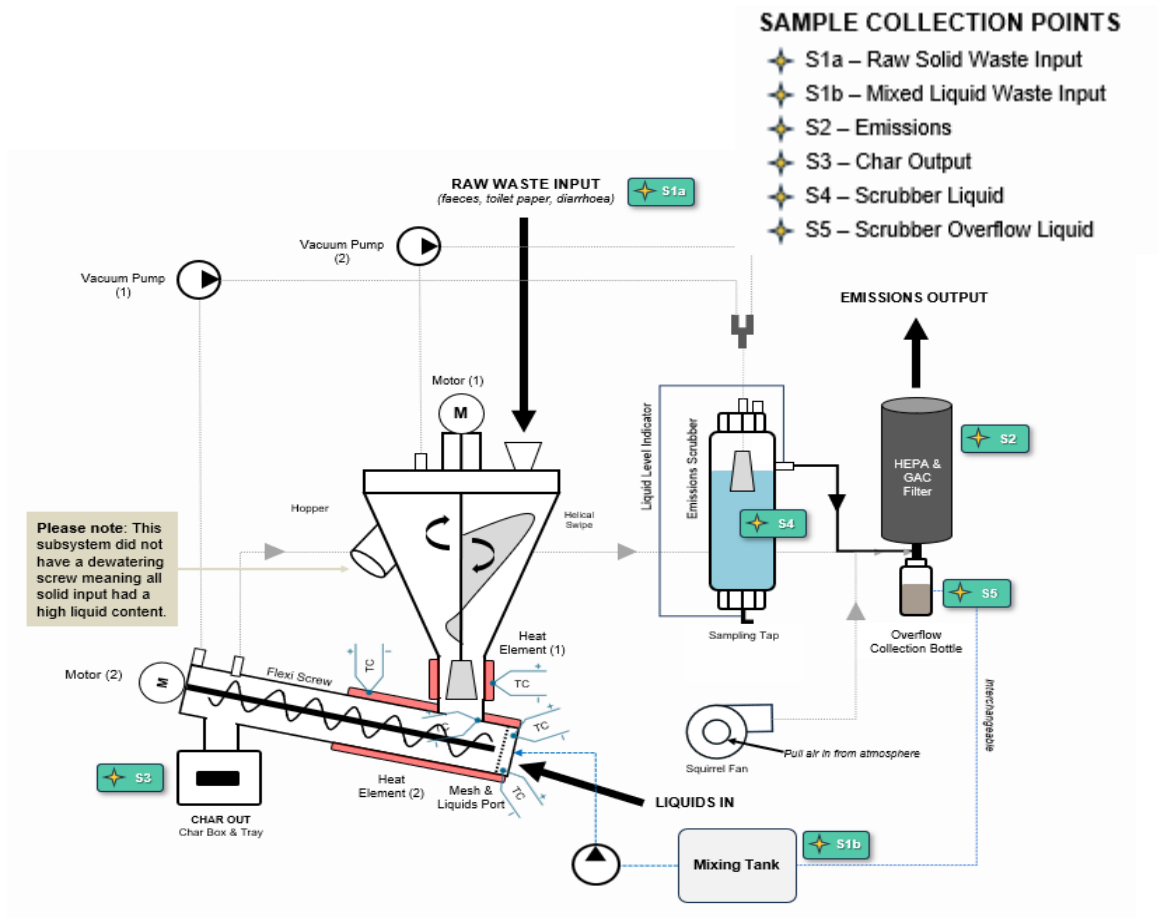


Figure 3-2 Human solid waste treatment subsystem diagram

This innovative system is designed to efficiently manage human waste through controlled thermal processing and automated liquid management.

3.1.1 Solid Management Process

The process began at the hopper, where the measured raw solids were introduced manually through the S1a input point. The helical swipe attached to the motor shaft (motor 1) encouraged the solids to move down towards the heating zone where torrefaction started (heat element 1). Once in the heating zone, the solids passed through a small clearance (around 1mm) around a metal grinder. The contact time of the solids in the heating zone and the temperature of the heat clamp were controlled by the motor shaft rotation speed and temperature settings determined through the firmware.

Torrefied materials (char) dropped into the horizontal chamber, where a metal screw powered by motor 2 conveyed them horizontally toward the char collection box (S3). The exterior of the chamber was wrapped with heating tape/heat element (2), ensuring further drying of the char. To maintain thermal efficiency, the entire processing path was fully insulated.

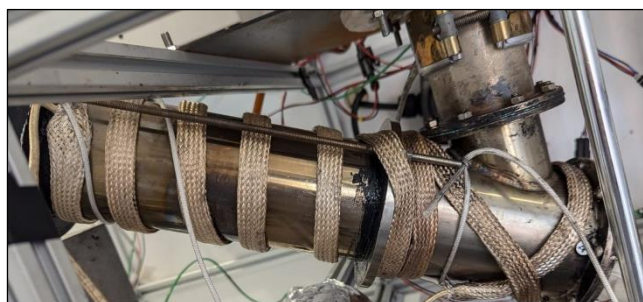


Figure 3-3 Heat tape installation around the chamber

The emission control system featured two vacuum pumps, each operating at 40% power. A Vacuum Pump (1) was positioned at the cylindrical chamber's top and another Vacuum Pump (2) was located at the hopper, directing gases through a water-based scrubber (S4) for volatile gas capture. Overflow (S5) from the scrubber flowed into a mixing tank (S1b). An additional tube at the top of the cylindrical chamber facilitated the efficient extraction of condensed air. The system utilized a squirrel fan (50% power) that pulled in environmental air, creating a venturi effect for optimal gas flow. The gases were directed to a HEPA filter (S2) covered with GAC filter, with any condensate collected returning to the mixing tank via pipes. The HEPA filter captured airborne pathogens while the activated carbon layer enhanced odour absorption.

All motors and heat elements were controlled via a control box with a coding system. Thermocouples were installed to ensure optimal working conditions inside the system, during the thermal treatment.

3.1.2 Liquid Management Process

The primary purpose of the liquid management system was to handle all liquid waste generated within the entire system, as well as the liquid produced within the tested subsystem itself. This included unprocessed liquid from various stages

of the process, along with scrubber overflow and system condensate. By directing all liquid waste to the mixing tank (S1b) for evaporation, the system ensured efficient treatment and prevented liquid discharge. Utilizing heat from the thermal treatment process, this approach maintained a closed-loop operation, optimizing waste management and system efficiency.

The liquid management system operated through an automated control system. The raw liquid was added to the mixing tank (S1b), which also collected scrubber overflow and system condensate. The system received liquid via the bottom lid of the cylindrical chamber. A metal mesh was positioned near the lid to prevent solids from entering the liquid system. The liquid pump (20% power) controlled the liquid flow using two sensors: a minimum and a maximum sensor (Figure 3-3). The system utilized heat from the thermal treatment process to evaporate the liquid, ensuring zero liquid output from the system.

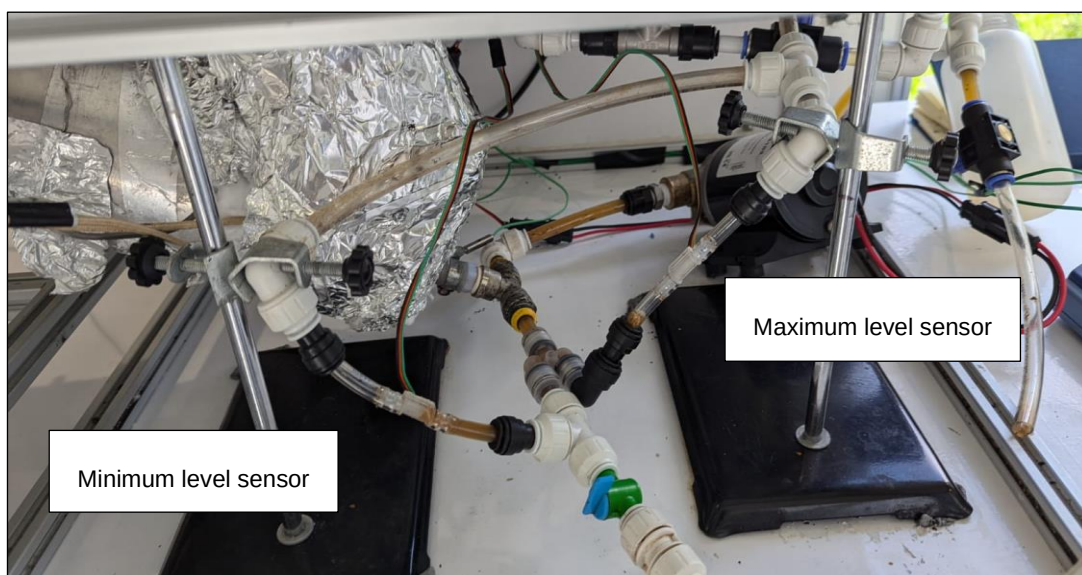


Figure 3-4 Automated liquid management system

Information related to the specific hardware components and testing equipment can be found in Table 3-1.

Table 3-1 Components and instruments

Component/Instrument	Specifications	Manufacturers' Part No.
Motors	Mellor Electric Brushed Geared DC Geared Motor, 24VDC, 17Nm, 5RPM	FBD1023
Heat Clamp (Torrefaction)	Heating Element, 415W, 230V AC	920-9966
Heat tape (Horizontal chamber)	Band Heater, 50mm, 560W, 230V AC	L7050C56A5
Liquid Pump	Jabsco Mini Puppy Self-Priming Pump 24V DC	23620-4003
Vacuum Pumps	Mini Vacuum Pump -85kPa, DC24V VN-C4 40L/min	N/A
Thermocouples	RS PRO Type K Thermocouple 150mm Length, 1.5mm Diameter à +1100°C	397-1236
Squirrel fan	24V, 16-28V/DC, 42W, 3000 min ⁻¹	G1G100-ABT7-02
Meter Reader	5 in 1 Water Quality Test Pen for pH, EC, TDS, Salinity and Temperature	EZ-9909SP
Gas detector	Gas Monitor, -20°C to +55°C	FZ-9909SP

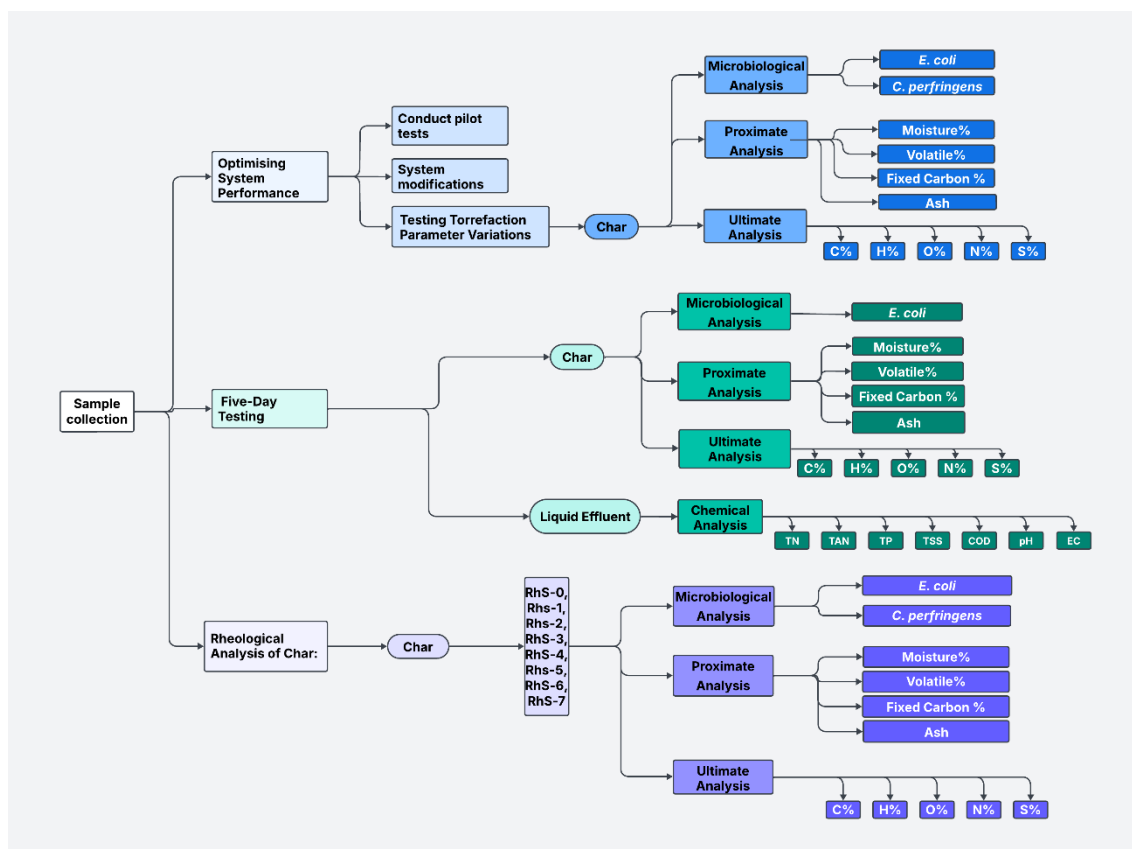


Figure 3-5 Overview of methodology

3.2 Sample Collection

The research utilized human solid waste collected anonymously through a specialized toilet facility at Cranfield University, open between 9:00 a.m. and 5:00 p.m. on working days. After each toilet use, the system flushed waste into a storage tank at the front end. Solid waste, including tissue, was manually separated from the liquid portion by opening the front end. All separated samples were stored at 4°C until testing.

3.3 Optimisation of System Performance and Biochar Quality

A series of tests were performed to evaluate the system performance under various operating conditions to optimise the human solid waste treatment system and ensure high-quality biochar output. The optimisation process involved three key steps, illustrated hereafter.

3.3.1 Conduct Pilot Tests to Understand System Behaviour

First, pilot tests were conducted to evaluate the effectiveness of the system, identify operating challenges, and examine the effects of critical parameters such as temperatures and motor rotation speeds. These tests assisted in recognising necessary component developments or alterations. Additionally, facilitated the assessment of gas emissions, thermal efficiency, and the overall char formation process.

3.3.2 System Modifications Based on Test Results

Several improvements were made to increase system performance and biochar quality. To validate these modifications, the system was re-evaluated using new test parameters. Significant changes included:

- Conveyance system adjustment: The metal spiral was replaced with a metal screw mechanism to improve horizontal upward movement of solids.
- Heating Element Reconfiguration: The heat clamp outside the horizontal chamber was removed, and the heat tape was expanded to provide more consistent heating.
- A squirrel fan was installed to create a venturi effect, improving airflow and optimizing gas extraction efficiency.
- Automated liquid management: Liquid feeding was introduced from the bottom of the chamber.

Initially, certain changes caused system failures, requiring more adjustments to optimise performance. The main challenge was that altering one system component required modifying every other system parameter. As a result, additional testing was required to determine the optimal parameters settings.

3.3.3 Testing Impact of Torrefaction Parameter Variations on Char Properties

Tests were performed by changing the heat element (1) temperature settings and motor (1) screw rotation speeds, to identify the optimal conditions for high-quality

biochar production. The tested conditions are included in the following Table 3-2. All other parameters can be found in Appendix B, Table B-1. For each test, 300 g of solid was used, and the feedstock was the same for all the tests. All the char samples were shipped to an external, certified laboratory for *E. coli* and *C. perfringens* quantification. Additionally, proximate and ultimate analyses were conducted to determine the chemical composition of the char samples.

Table 3-2 Heating and rotation conditions tested for char formation optimisation

Test	Heat element (1) temperature (°C)	Motor (1) rotation speed (RPM)
1	150	0.11
2	150	0.22
3	200	0.11
4	200	0.22

3.4 System Performance Evaluation Under Continuous Operation (Five-Day Testing)

This testing method evaluated how well the system performed under controlled, real-world conditions. The five-day continuous testing was conducted to thoroughly assess the torrefaction system's performance by mimicking a waste processing situation at the family level (five members).

Prior to operation, the system was preheated for 15 minutes to reach the desired temperature. The scrubber was filled with 2300 ml of water. The experimental approach followed ISO recommendations, with 1.5 kg of solids added daily (same feedstock), representing approximately 300g per person for a family of five. The input was strategically distributed throughout the day: 35% (525g) in the morning, 25% (375g) in the afternoon, and 40% (600g) in the evening to mimic realistic human waste generation patterns (IBS ISO 30500:2018, 2018). Each day, 300 mL of liquid was added to the mixing tank to evaluate the system's evaporation capacity.

Torrefaction was carried out at 250°C (heat element 1) and rotational speed of 0.083 RPM (motor 1). The selection of temperature and rotation velocity values was driven by findings from preliminary tests. All other operation parameters can be found in Appendix B, Table B-2. Each day, the system operated continuously for 6 hours.

At the end of the day, samples were collected from designated collection points for comprehensive laboratory analyses: raw solid input (S1a), raw liquid (S1b), char output (S3), scrubber liquid (S4). Pathogens testing was conducted on raw solid samples and char output to determine the bacterial *E. coli* levels. Proximate and ultimate analyses were performed on char samples to characterise their chemical composition. Additionally, effluent samples (Raw liquid and scrubber liquid) underwent chemical analyses, including tests for chemical oxygen demand (COD), total suspended solids (TSS), pH, electrical conductivity (EC), total nitrogen (TN), total ammonia nitrogen (TAN), and total phosphorus (TP), to ensure compliance with environmental standards (IBS ISO 30500:2018, 2018). Additionally, the liquid evaporation volume was measured, and the liquid evaporation rate (ml/hr) was calculated as shown in **Eq. 1**

$$\text{Liquid Evaporation Rate} = \frac{\text{Liquid Evaporation Volume (mL)}}{\text{Process time (hr)}} \quad \text{Eq. 1}$$

3.5 Rheological Analysis of Char: Properties and Trends

During continuous testing of the torrefaction system, char samples were collected and analysed to create a detailed rheology chart. The different rheological states labelled RhS-0 to RhS-7, were defined based on observations and testing of the char at various stages. A classification system was established to follow the evolution of the raw material to fully converted char, through the study of its physical, thermal, and mechanical properties. Furthermore, proximate and ultimate analyses were performed to characterize the chemical compositions at different rheological states. Microbial properties and safety parameters of *E. coli*

and *C. perfringens* tests were also determined. The resulting char rheology chart that combined the distinct aspects of physical, chemical, and biological data, is irreplaceable to our understanding of the complex, interlinked nature of torrefaction and structural changes at the molecular scale that are integral to the thermal conversion of biomass materials for process optimization and quality control.

3.6 ISO 30500 recommended test methods for outputs

To verify that the system conforms to internationally recognised safety and quality requirements, outputs were assessed adopting internationally recognised test methodologies. The testing focused on the solid output and the effluent. Gas emissions (CO, CO₂, H₂S, CH₄, O₂) were measured using gas detectors.

3.6.1 Pathogen Testing Method for Solid Output

The bacterial pathogen test was performed using *E. coli* as a surrogate, with levels measured in MPN (Most Probable Number) adhering to the standardized APHA 9221, APHA 9222, and APHA 9223 methods. The aim was to reduce *E. coli* levels below 100 MPN/g dry solids.

The protozoan pathogen test was carried out using *C. perfringens* spores as a surrogate, with concentrations measured in CFU (Colony-Forming Units) following standardized microbiological methods (for solids: ISO 7937; for liquids: ISO 14189). It was aimed to reduce *C. perfringens* spore levels below 1 CFU/g dry solids.

For validation, tests were conducted up to three times, and the values were recorded.

The analysis was conducted by an external, certified laboratory within the framework of ISO environmental standards, with specific attention to the limitations and threshold values outlined in Appendix C (5C.1).

3.6.2 Chemical Analysis for Effluent

The effluent from the torrefaction system underwent a thorough series of analytical tests to determine its chemical characteristics. Several parameters were systematically assessed via recommended methods, including electrical conductivity, pH (APHA 4500-H+ A), total nitrogen (TN) (APHA 4500-N C), total phosphorus (TP) (APHA 4500-P), chemical oxygen demand (COD) (APHA 5220 B), total suspended solids (TSS) (APHA 2540D), and total ammonia nitrogen (TAN) (APHA 4500-NH₃ F). These analyses were conducted using standard methodological protocols to ensure accurate and reproducible results. To validate the data, each test was performed up to three times, and the average value was recorded.

The analysis was conducted within the framework of ISO environmental standards, with specific attention to the limitations and threshold values outlined in Appendix C (5C.2.).

3.6.3 Chemical Analysis for Solid Output

3.6.3.1 Proximate Analysis

The content of moisture, ash, fixed carbon (FC), and volatile matter (VM) of the biochar samples were quantified in triplicate by thermogravimetric analysis (TGA Q500, TA Instruments, USA), following a previously described method that was adapted to the ASTM standard (Choi et al., 2014).

Initially, the sample was heated to 105°C at a rate of 40°C/min and held for 15 minutes in a nitrogen (N₂) atmosphere to remove moisture. Then, the temperature was increased to 900°C at a heating rate of 40°C/min and maintained at 900°C for 30 minutes under N₂. Afterward, the purge gas was switched to oxygen (O₂), and the sample was held at 900°C for 15 minutes to combust the remaining fixed carbon. Finally, the system was cooled down to 35°C at 40°C/min. For validation, each test was conducted up to three times, and the average value was recorded.

3.6.3.2 Ultimate Analysis

The ultimate analysis of the char samples was performed using a CHNS analyser, (Vario EL CUBE, Elementar, Germany) through the total oxidation method (Reza et al., 2019). Prior to analysis, samples were oven-dried at 105 °C for 24 hours, ground, and then subjected to elemental analysis. The results for carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) are reported on a dry basis. The percentages of carbon (C%), nitrogen (N%), hydrogen (H%), and sulphur (S%) were analysed. The oxygen percentage (O%) was calculated by subtracting the total CHNS percentages from 100 (Eq. 2).

$$\text{Oxygen Content (\%)} = 100 - (C\% + H\% + N\% + S\%) \quad \text{Eq. 2}$$

For validation, each test was conducted up to three times, and the average value was recorded.

4 Results and Discussion

4.1 Impact of Torrefaction Parameter Variations on Char Properties

4.1.1 Physical Properties of Biochar

The physical appearance of the biochar samples obtained at different torrefaction conditions are shown in Figure 4-1.

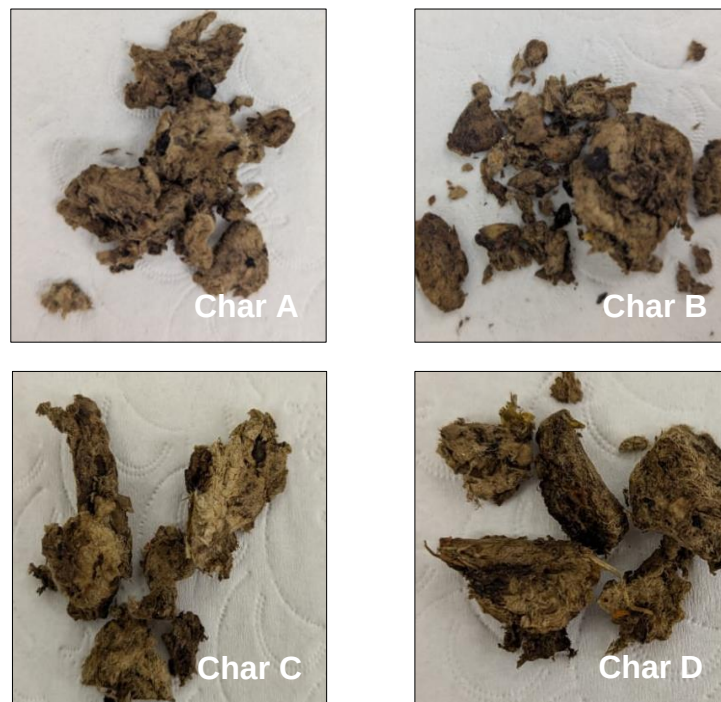


Figure 4-1 The physical appearance of the biochar samples at different torrefaction temperatures and rotation speeds. Char A: 150°C, 0.11 RPM; Char B: 150°C, 0.22 RPM; Char C: 200°C, 0.11 RPM; Char D: 200°C, 0.22 RPM

The properties of biochar vary depending on the system conditions and the characteristics of the raw input. In this study, only temperature (heat element 1) and retention time (motor 1 rotation speed) impact on the biochar properties were assessed, as all other system conditions and the raw input remained constant across the four test scenarios. However, all four char samples ultimately showed

relatively similar characteristics with a moist, hydrophilic, brown colour, and non-grindable texture Figure 4-1.

As expected, an increase in torrefaction temperature resulted in a lower moisture level in the biochar. Biochar produced at 200°C (Char C and Char D) appeared slightly drier than torrefied at 150°C (Char A and Char B). It has been reported in the literature that prolonged holding times may somewhat improve the quality of the biochar (Ilango & Lefebvre, 2016), yet, in this test, when comparing rotation speeds at the same temperature, no major differences in physical appearance were observed between Char A and Char B (150°C) or Char C and Char D (200°C). This aligned with the expectation that torrefaction temperature plays a key role in determining moisture content (Tumuluru, 2016).

All biochar samples exhibited hydrophilic properties due to the low temperatures used in this test. Research has shown that hydrophobicity improved progressively with increasing torrefaction temperatures (Jeong et al., 2019). Similarly, (Dyjakon et al., 2019) found that torrefaction of food waste biomass at temperatures ranging from 200°C to 280°C led to a steady increase in the hydrophobic properties with rising temperature. Torrefied biochar often has hydrophobic qualities and a dry texture (Serio et al., 2016) The generated biochar was moist and had hydrophilic properties, thus suggesting that these char samples might not have been sufficiently torrefied. This implies that additional optimisation of the torrefaction conditions employed in this investigation may be necessary.

4.1.2 Microbiological Analysis for Solid Output

The contents of *E. coli* and *C. perfringens* in the generated biochar samples are reported in Table 4-1.

Table 4-1 *E. coli* and *C. perfringens* levels in biochar generated under varying torrefaction parameters

Torrefaction Parameters		<i>E.coli</i> (MPN/g dry solids)	<i>C. perfringens</i> (CFU/g dry solids)
Temperature (°C)	Motor Rotation Speed (RPM)		
150	0.11	<10	20
	0.22	<10	30
200	0.11	<10	<10
	0.22	<10	<10
Raw Solid		>24200	>1000

All biochar samples (Char A, Char B, Char C, and Char D) had *E. coli* levels below 10 MPN/g, indicating effective reduction during torrefaction when compared with the *E.coli* value of the raw solids >24200 MPN/g (Table 4-1).

For *C. perfringens*, the pathogenic level of raw sample was >1000 CFU/g. Biochar torrefied at 150°C exhibited contamination levels of 20 CFU/g at 0.11 RPM and 30 CFU/g at 0.22 RPM, suggesting that high retention time (low RPM) contributed to a greater pathogenic reduction. Biochar produced at 200°C showed significantly lower contamination levels, with <10 CFU/g at both 0.11 RPM and 0.22 RPM levels. These results indicate that higher torrefaction temperatures generally enhance pathogen reduction. Additionally, retention time also played a significant role in influencing pathogen levels.

Studies examining the direct impact of torrefaction parameters (temperature and residence time) on pathogen levels are limited. However, since torrefaction operates at significantly higher temperatures than those required to inactivate common pathogens, it is likely effective in eliminating them. For instance, *E. coli* is effectively destroyed at a minimum temperature of 71°C, while significant inactivation of *C. perfringens* spores can be achieved by exposing them to high temperatures for a longer period (Clay, 2017; Talukdar et al., 2017). Research indicates that more than 90% of *C. perfringens* spores were inactivated when incubated in water at 90 to 100°C for 10 to 30 minutes (Talukdar et al., 2017) .

All biochar samples contained *E. coli* levels below 10 MPN/g, which was far below the maximum permitted limit, which is 100 MPN/g for *E. coli* (human intestinal bacteria) as per the ISO 30500 standard. This suggested that the torrefaction parameters are sufficient to regulate the levels of *E. coli*.

The ISO standard sets a maximum level of 1 CFU/g for *C.perfringens* (human intestinal protozoa). However, the results for every biochar sample revealed concentrations over this threshold. As a result, *C. perfringens* cannot be reduced to acceptable levels using the torrefaction parameters tested in this study. Torrefaction parameters must be changed to achieve greater reduction of *C. perfringens*, to ensure higher char quality for safe disposal or reuse.

4.1.3 Proximate Analysis Data for Char Samples

The proximate composition of biochar, including moisture content, volatile matter, fixed carbon percentage and ash content is present in Table 4-2.

Table 4-2 Proximate analysis of biochar samples produced under varying torrefaction parameters

Torrefaction Parameters		Moisture %	Volatile %	Fixed Carbon%	Ash %
Temperature (°C)	RPM				
150	0.11	5±0.005	76±0.010	15±0.005	5±0.005
	0.22	14±0.005	69±0.028	12±0.004	5±0.013
200	0.11	3±0.005	78±0.005	13±0.006	6±0.005
	0.22	3±0.005	85±0.050	7±0.055	5±0.017

The impact of rotation speed and torrefaction temperature on the biochar moisture content is depicted in Figure 4-2.

Torrefaction Parameters	
Temperature (°C)	Rotation Speed (RPM)
150	0.11
	0.22
200	0.11
	0.22

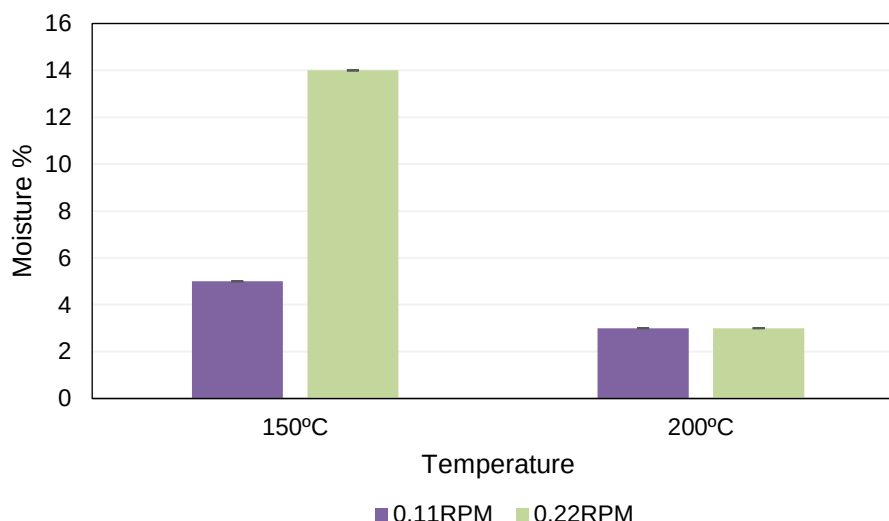


Figure 4-2 Effect of temperature (°C) and rotation speeds (RPM) on moisture% in char output

The data shows that increasing the torrefaction temperature from 150°C to 200°C significantly reduced moisture content. At 150°C, the moisture content was 5% and 14% at 0.11 rpm and 0.22 rpm, respectively. At 200°C, the moisture content was 3% at both 0.11 RPM and 0.22 RPM. (Bridgeman et al., 2008) examined torrefaction of two energy crops, reed canary grass and short rotation willow coppice, at temperatures ranging from 229–289°C and confirmed that increasing the temperature had a positive effect on the thermal decomposition of the biomass. The moisture content at 150°C varies between the two RPMs, showing that a higher RPM (smaller retention time) leads to increased moisture content. This confirms that retention time influences char properties, including moisture content (Ilango & Lefebvre, 2016). However, at 200°C, for both rotation speeds the moisture content was 3%. A previous study suggested that holding time may influence the char outcomes at lower operation temperatures, but this effect becomes negligible at higher temperatures, when dehydration occurs extremely fast (Baldock & Smernik, n.d.).

The impact of rotation speed and torrefaction temperature on the biochar volatile content is depicted in Figure 4-3.

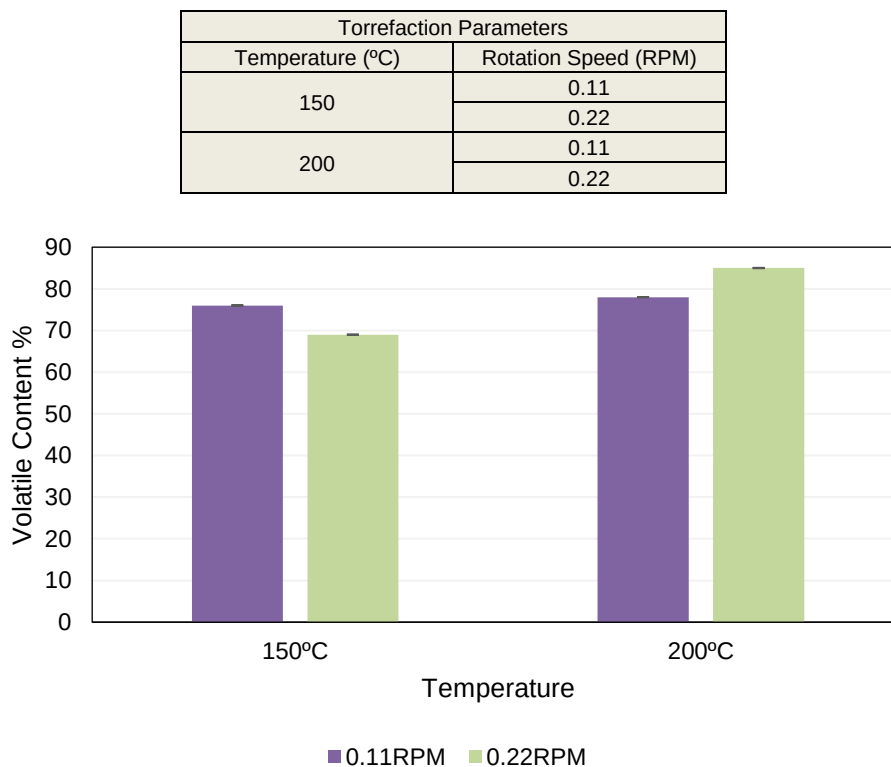


Figure 4-3 Effect of temperature (°C) and rotation speeds (RPM) on volatile content % in char output

For all samples, the volatile content is relatively high due to the lower torrefaction temperatures used. Studies indicate that hemicellulose starts decomposing between 130–260°C (Tumuluru, et al., 2011). Temperatures below 300°C, which is the typical upper limit for torrefaction, facilitate only around 50% of the pyrolytic water evolution and do not result in a significant release of most of other gases or tars. However, exceptions include the release of acetic acid and modest amounts of CO₂ and CO (Serio et al., 2016).

In this study, the volatile content (85–69%) at different temperatures and rotation speeds did not differ remarkably (Figure 4-3). Similarly, the fixed carbon content (15–7%) (Figure 4-4) and ash content (6–5%) (Figure 4-5) remained relatively

constant across the tested conditions. This may be due to the relatively low temperatures, resulting in minimal chemical conversion.

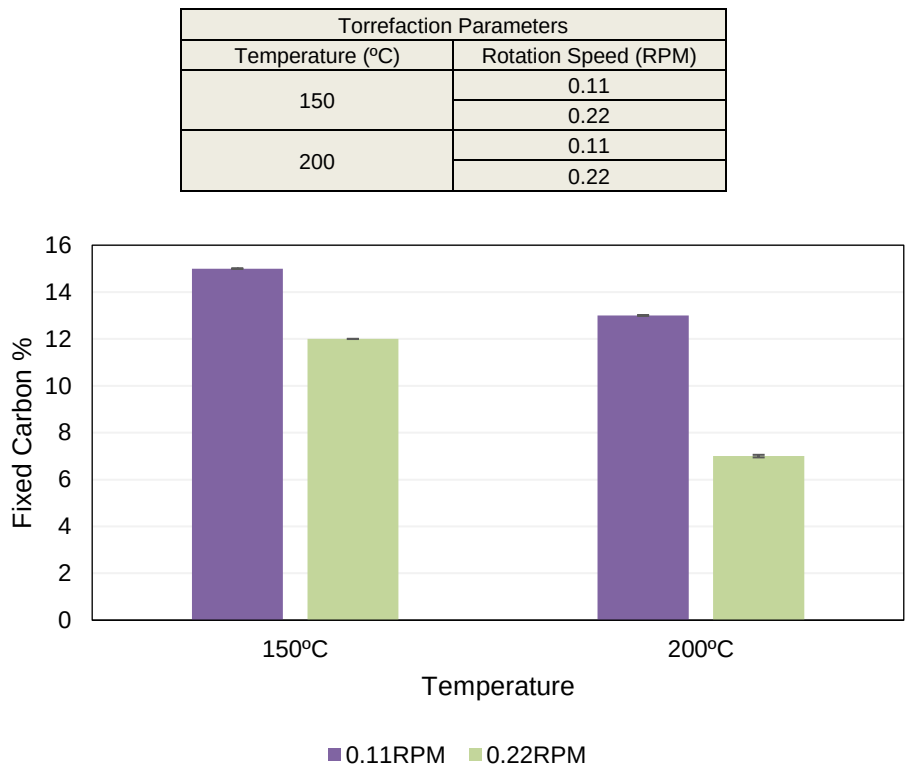


Figure 4-4 Effect of temperature (°C) and rotation speeds (RPM) on fixed carbon % in char output

Torrefaction Parameters	
Temperature (°C)	Rotation Speed (RPM)
150	0.11
	0.22
200	0.11
	0.22

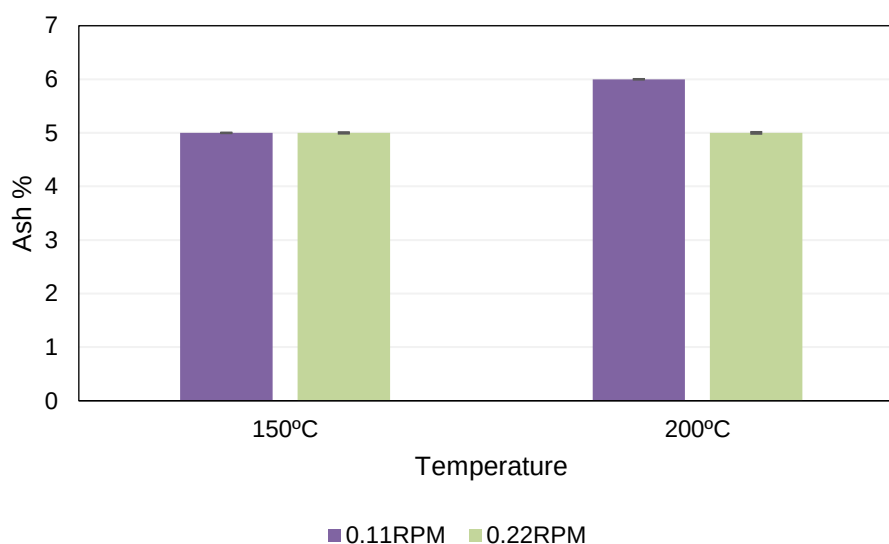


Figure 4-5 Effect of temperature (°C) and rotation speeds (RPM) on ash % in char output

4.1.4 Ultimate Analysis

The elemental composition data, including carbon (C), nitrogen (N), oxygen (O), phosphorus (P), and sulphur (S) levels in biochar samples produced under different torrefaction scenarios, is presented in **Table 4-3**.

Table 4-3 Elemental composition of biochar samples at different torrefaction conditions

Torrefaction Parameters		N%	C%	H%	S%	O%
Temperature (°C)	RPM					
150	0.11	1.327±0.159	47.340±0.228	8.317±0.071	0.087±0.010	42.930±0.122
	0.22	1.083±0.077	46.340±0.466	7.970±0.063	0.078±0.002	44.529±0.485
200	0.11	1.947±0.100	50.440±0.320	8.643±0.280	0.132±0.020	38.838±0.600
	0.22	1.690±0.206	47.003±0.327	7.834±0.255	0.129±0.022	43.344±0.468

Torrefaction Parameters	
Temperature (°C)	Rotation Speed (RPM)
150	0.11
	0.22
200	0.11
	0.22

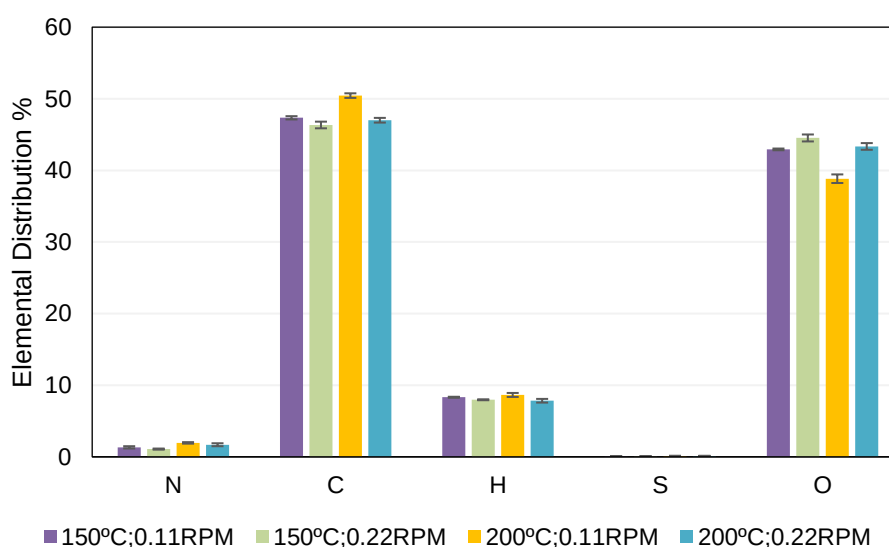


Figure 4-6 Percentage distribution of elements in biochar samples under varying torrefaction conditions

All four biochar samples exhibited a high carbon (C) content (>46%), followed by oxygen (O) as the second most abundant element. The samples contained

lower levels of hydrogen (H) and nitrogen (N), while sulphur (S) was present in very small quantities (<0.132%) (Figure 4-6).

Higher torrefaction temperatures and retention time help retain carbon content due to enhanced thermal degradation of volatiles and carbon concentration through mass loss (Tumuluru, et al., 2011). This is aligned with the current study, where carbon percentage increased slightly with an increase in temperature and retention time. To illustrate, at 150°C, the C content was increased from 46.34% (0.22 RPM) to 47.34% (0.11 RPM), whereas at 200°C, it increased from 47.00% (0.22 RPM) to 50.44% (0.11 RPM).

Nitrogen content increased with the temperature and retention time. Thus, while nitrogen at 150°C increased from 1.083% (0.22 RPM) to 1.327% (0.11 RPM), nitrogen levels at 200°C ranged from 1.690% (0.22) to 1.947% (0.11). This trend could indicate that higher temperatures promoted the decomposition of organic material, causing the release of volatile compounds, whereas nitrogen-rich compounds (such as proteins and amino acids) tended to remain in the solid phase (Tumuluru, et al., 2011).

The hydrogen and oxygen content followed a similar trend, remaining relatively constant regardless of temperature or retention time. Across the scenarios, the hydrogen content ranged between 8.643% and 7.834%, while the oxygen content varied from 44.529% to 38.838%. The sulphur content also showed slight variation across different conditions, but it increased with temperature. At 150°C, sulphur content ranged from 0.087% to 0.11% (for 0.11 and 0.22 rpm, respectively), and at 200°C, it ranged from 0.132% to 0.129% (for 0.11 and 0.22 rpm, respectively). However, in all cases, sulphur content remained below 0.2%.

Comparable data has been previously reported for 200°C torrefied char from human faeces, with the following composition: C 41.71%, H 5.22%, and S 0.52%. However, the oxygen and nitrogen content were slightly higher at 25.77% and 4.07% respectively, which may be due to variations in the feedstock composition (Serio et al., 2016).

4.2 System Performance Evaluation Under Continuous Operation (Five-Day Testing)

During the testing period, the system processed liquid and solid waste streams without failure and used safe treatment and effective processing. The daily observations and findings confirm that the system can consistently process raw waste feed continuously and is safe to be operated at home for family of up to five members.

4.2.1 Solid Output (Biochar) Analysis

4.2.1.1 Physical Properties of Biochar



Figure 4-7 The physical appearance of biochar samples collected over five days at a torrefaction temperature of 250°C and a rotation speed of 0.083 RPM

Photographs of the biochar samples taken on each testing day (August 27–30 and September 2, 2024) are shown in Figure 4-7 The physical appearance of biochar samples collected over five days at a torrefaction temperature of 250°C and a rotation speed of 0.083 RPM, demonstrating the char output's physical characteristics.

The biochar produced at 250°C with a rotation speed of 0.083 RPM consistently exhibited a less moist, brittle, grindable texture, dark brown colour, and hydrophobic nature across all five testing days. This consistency confirmed the stability of the torrefaction process to produce a uniform output.

The hydrophobic characteristics of the biochar agreed with the previous studies on torrefied biomass. Dyjakon et al., (2019) reported that the biomass possessed hydrophilic characteristics at 105°C and intermediate hydrophilic characteristics at 240°C. 250°C is generally considered the most effective temperature of

torrefaction, and it's been widely documented that it can yield biochars with stable properties. Wang et al., (2011) observed that the use of an optimal torrefaction temperature of 230– 250°C with a residence time of 30 minutes improved the energy yield of cotton stalk and wheat straw as well as their grindability. Similarly, Chen et al., (2011) studied the torrefaction of wood briquettes in the 220–270°C range, finding that the optimal range for the energy yield was from 250 to 270°C. Moreover, Chen et al., (2011) reported that the grindability significantly improved when wood biomass was torrefied at 250°C for more than an hour.

4.2.1.2 Microbiological Analysis for Solid Output

The *E. coli* concentrations (MPN/g) for both raw solid input and biochar output over a five-day period are shown in Table 4-4.

Table 4-4 *E. coli* concentration in solid samples

Date	Sample	<i>E.Coli</i> (MPN/g dry solids)
Day 1	Raw Solid Input	>241960
	Char Output	<10
Day 2	Raw Solid Input	>24196
	Char Output	<10
Day 3	Raw Solid Input	>241960
	Char Output	<10
Day 4	Raw Solid Input	>241960
	Char Output	<10
Day 5	Raw Solid Input	>241960
	Char Output	<10

The data highlighted a significant reduction in *E. coli* concentrations, with the raw solid input showing high contamination levels (>241960 MPN/g), while the treated biochar output consistently maintained levels below 10 MPN/g.

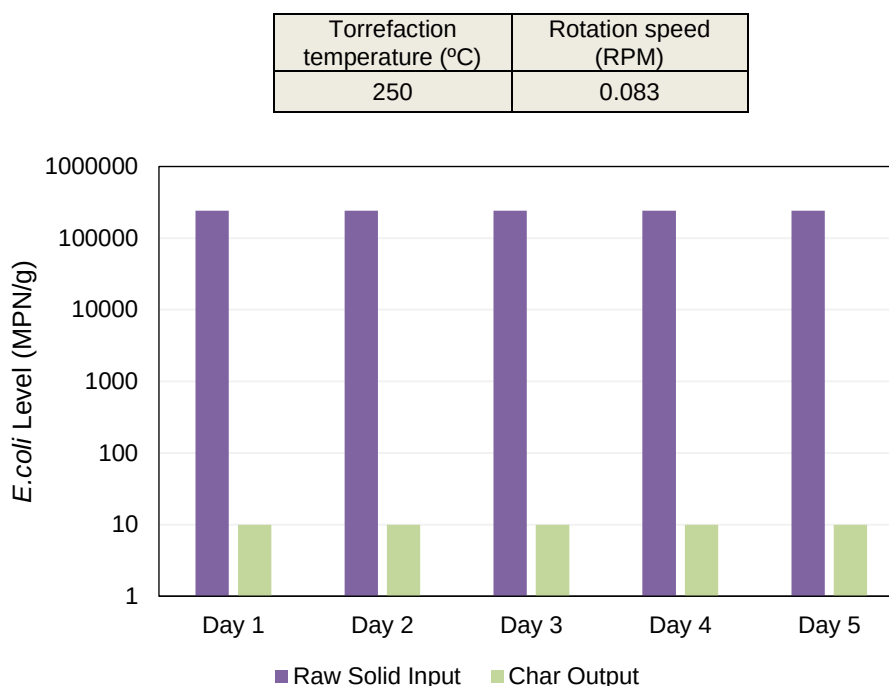


Figure 4-8 *E. coli* reduction in char output over five testing days

Over the five testing days, the system continuously produced a significant reduction in *E. coli* levels, as shown in Figure 4-8. This represented an impressive pathogen reduction of 99.99%, obtaining concentrations far below the ISO 30500 safety threshold of 100 MPN/g. This substantial reduction confirms the system's reliability in achieving safe sanitation standards.

4.2.1.3 Proximate Analysis Data for Char Samples

The proximate analysis results for three char samples collected from five testing days are presented in Table 4-5. Only three samples (day 1, day 3 and day 5) were analysed as all the char samples exhibited similar physical characteristics.

Table 4-5 Proximate analysis of biochar samples collected on day 1, day 3 and day 5

Char Samples	Moisture %	Volatile %	Fixed Carbon %	Ash %
Day 1	5±0.005	79±0.005	9±0.020	7±0.023
Day 3	5±0.020	75±0.020	11±0.011	9±0.011
Day 5	5±0.005	74±0.005	10±0.005	11±0.005

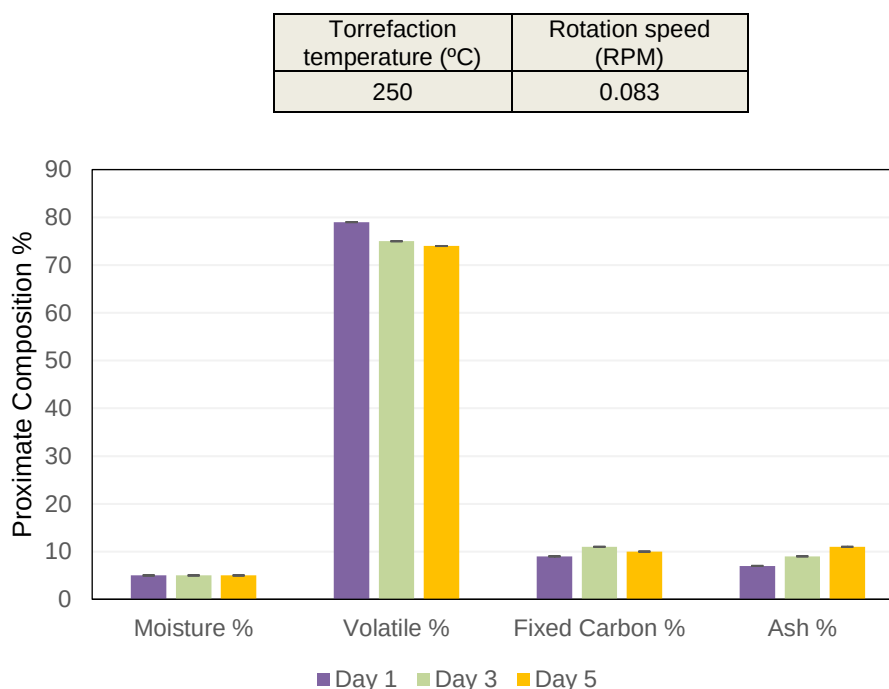


Figure 4-9 Percentage of moisture, volatile matter, ash, and fixed carbon of char samples collected on day 1, day 3, and day 5.

The data shows a relatively consistent distribution of proximate components across different test days. Overall, the proximate analysis results indicated that all the samples contained greater volatile matter contents (>74%), whereas ash content (<11%) & fixed carbon content (<11%) were present in lower amounts.

Torrefaction at 250°C has been widely studied for various biomass materials, and the results of this study aligned with previous research in several aspects. (Granados et al., 2014) performed torrefaction of seven agricultural residues (palm oil fiber, banana rachis, sugarcane bagasse, rice husk, sawdust, and coffee residue), reporting contents of 4-6% moisture, 56-88% volatile matter, 2-24% ash, and 2-17% fixed carbon. In a similar study, Deng et al. (2009) found that rice straw had a moisture content of 5.12%, volatile matter of 68.83%, fixed carbon of 17.46%, and ash content of 8.59%. The results demonstrated that torrefaction was effective at reducing the moisture content to below 5%, consistent with the available literature. In addition, previous studies suggested that increased volatile matter corresponds with reduced fixed carbon. This was evident from the findings of this study, which showed that the volatile material was between 74–79%, while the fixed carbon was in the range of 9–11%. These findings contributed to

characterise torrefaction performance at 250°C, reinforcing established trends while highlighting specific deviations influenced by the process conditions.

4.2.1.4 Ultimate Analysis

The ultimate analysis provided elemental composition data, including carbon (C), nitrogen (N), oxygen (O), and phosphorus (P) levels in biochar. The ultimate analysis value for the three char samples (day 1, day 3, day 5) are shown in Table 4-6.

Table 4-6 Elementary analysis of biochar samples collected on day 1, day 3 and day 5

Char Samples	N %	C %	H%	S%	O%
Day 1	3.107±0.240	47.750±0.650	7.947±0.260	0.341±0.040	40.855±0.900
Day 3	2.997±0.064	48.477±0.023	5.276±1.030	0.437±0.193	42.814±0.808
Day 5	3.263±0.113	50.537±0.330	8.130±0.080	0.281±0.004	37.788±0.338

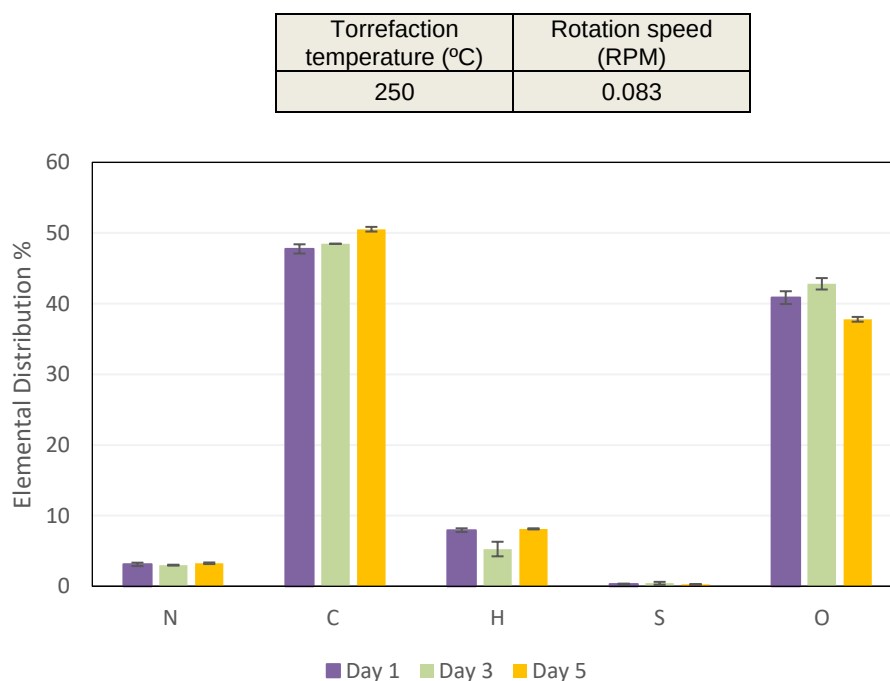


Figure 4-10 Percentage distribution of elements in biochar samples collected on day 1, day 3, and day 5

The elemental analysis across all three days showed consistent patterns. Carbon (C) was always the most abundant element in all samples (47-51%), followed by

the second most abundant (37-43%) as oxygen (O). The samples had a low level of hydrogen (H) at about 5-8% and a smaller concentration of nitrogen (N) at 0.3-0.5%, and sulphur (S) at less than 0.5%. Comparable results were documented in the literature of torrefied biomass, such as wood treated at 250°C (51.3% C, 40.9% O, 5.9% H, 0.4% N) as well as palm kernel shell processed at 250°C (52.13% C, 41.85% O, 5.52% H, 0.51% N) (Ma et al., 2017).

4.2.2 Chemical and Biological Properties in Liquid Effluent

The management of liquid effluents from torrefaction is crucial due to potential environmental impacts. Liquid condensates can be acidic and may contain hazardous organic compounds, requiring proper handling and disposal to prevent soil and water contamination.

According to Chen et al., (2018), the liquid products from torrefaction at 250°C are mainly composed of water and functionalized compounds, including acids, furans, ketones, aldehydes, and phenols, originating from the volatile components in hemicellulose and cellulose, as well as the partial degradation of lignin.

Table 4-7 summarizes the chemical and biological analyses results for liquid input and output (scrubber liquid) over multiple test days, focusing on key wastewater parameters such as the concentration of total nitrogen (TN), total ammonia nitrogen (TAN), total suspended solids (TSS), chemical oxygen demand (COD), total phosphorus (TP), pH, electrical conductivity (EC), and *E. coli* levels.

Table 4-7 Chemical characteristics of the effluent

Day	Sample	TN	TAN	TSS	COD	TP	pH	EC
		mg/L	mg/L	mg/L	mg/L	mg/L		μS/cm
Day 1	Raw Liquid Input	4560	1840	3140	5700	115	9	>1990
	Scrubber Liquid	119	62	10	156	<0.5	8	530
Day 2	Raw Liquid Input	4560	1840	3140	5700	115	9	>1990
	Scrubber Liquid	>150	156	140	430	1.1	8	950
Day 3	Raw Liquid Input	>6000	2460	2240	3040	65	9	>1990
	Scrubber Liquid	>150	132	80	315	0.4	9	910
Day 4	Raw Liquid Input	>6000	2460	2240	3040	65	9	>1990
	Scrubber Liquid	>150	117	40	183	<0.5	9	850
Day 5	Raw Liquid Input	>6000	2460	2240	3040	65	9	>1990
	Scrubber Liquid	>150	269	50	728	0.8	9	1260

Table 4-8 presents the reduction efficiency of TAN and TP in the scrubber liquid.

Table 4-8 Reduction Efficiency of TAN and TP in Scrubber liquid

Date	TAN Reduction %	TP Reduction %
Day 1	96.60%	99.60%
Day 2	91.50%	99.00%
Day 3	94.60%	99.40%
Day 4	95.20%	99.20%
Day 5	89.10%	98.80%

Human wastes consist of concentrated organic substances, nitrogenous compounds, and microbial biomass, which may significantly contribute to high nitrogen content in the feedstock. Proteins and nitrogenous compounds are hydrolysed during the hydrothermal process, resulting in soluble ammonia that

transfers to the process liquid. The liquid effluent can contain ammonia nitrogen (NH_3), organic nitrogen (nitrogen in amino acids and proteins), nitrite (NO_2^-) and nitrate (NO_3^-) (Mishra et al., 2022).

In this study, in the untreated liquid input TN concentrations were consistently high with values between 4560 and >6000 mg/L, and TAN values between 1840 and 2460 mg/L. TN levels in the scrubber liquid were generally below 150 mg/L and TAN values were between 62 and 269 mg/L.

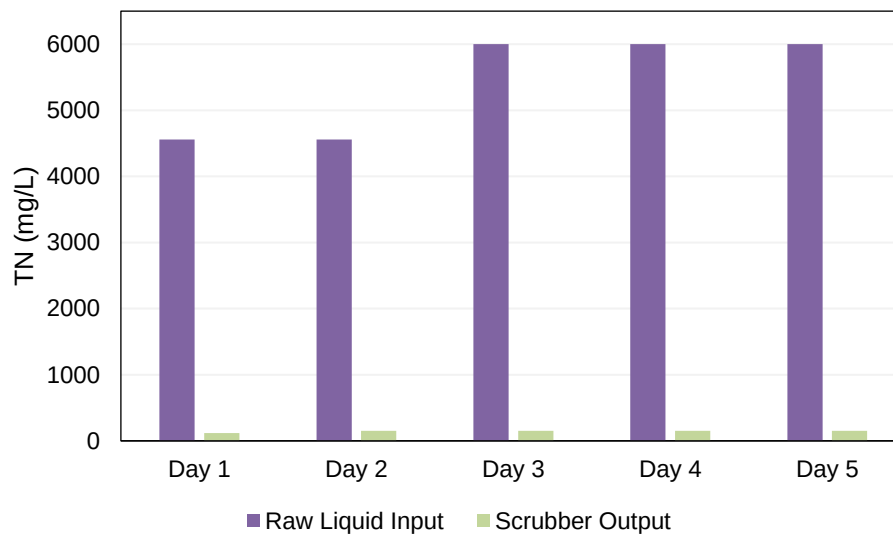


Figure 4-11 Total nitrogen (TN) concentrations in raw input and scrubber liquid over five days

Figure 4-12 shows the total ammonia nitrogen (TAN) concentrations in both the raw input and scrubber liquid, along with the percentage reduction of TAN in the scrubber liquid.

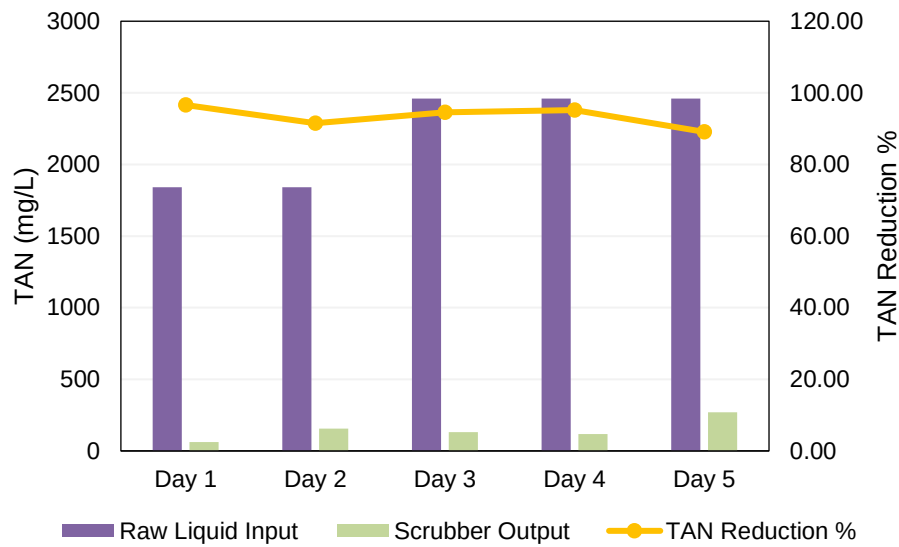


Figure 4-12 Total ammonia nitrogen (TAN) concentrations in raw input and scrubber liquid and TAN reduction % in scrubber liquid over five days

Phosphorus in the liquid effluent, resulting from processes like faeces torrefaction, exists in both inorganic forms (e.g., phosphates) and organic forms (e.g., organic molecules). Elevated levels of phosphorus in wastewater can have detrimental environmental impacts, primarily due to its role in promoting eutrophication (Tuser, 2022).

Figure 4-13 displays the total phosphorus (TP) concentrations in both the raw input and scrubber liquid, along with the percentage reduction of TP in the scrubber liquid.

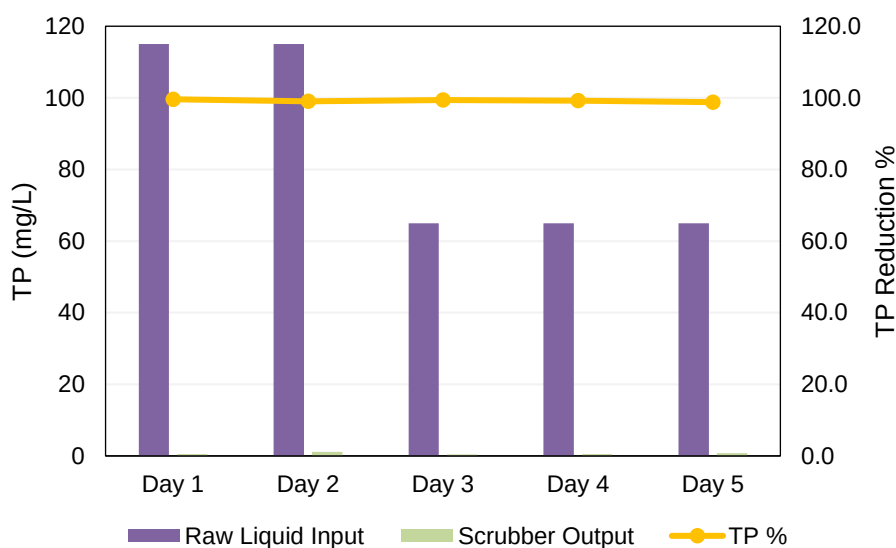


Figure 4-13 Total phosphorous (TP) concentrations in raw input and scrubber liquid and TP reduction % of scrubber liquid over five days

TP concentration in the raw liquid input varied between 65 and 115 mg/L. The scrubber liquid, showed much lower TP levels, ranging from less than 0.5 mg/L to 1.1 mg/L.

Table 4-8 highlights the system's efficiency in reducing total ammonia nitrogen and phosphorus levels as the scrubber liquid, achieving a high reduction percentage of TAN 93.40% and TP 99.20%. According to ISO 30500 total maximum nitrogen content in output liquid effluent is 70% and total phosphorus 80%. In this study, the reduction percentages of liquid effluent TN and TP are within a favourable range (BS ISO 30500:2018, 2018).

Figure 4-14 presents the total suspended solids (TSS) concentrations in both the raw input and scrubber liquid over a five-day period.

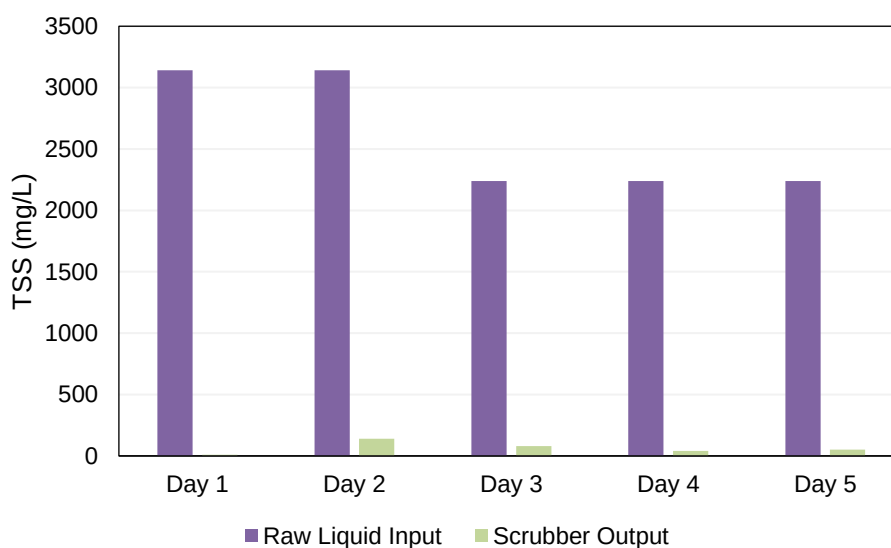


Figure 4-14 Total suspended solids (TSS) concentrations in raw input and scrubber liquid over five days

TSS are solid particles in water that do not dissolve and can be filtered out with appropriate mesh-size membranes. Elevated TSS levels can cause a loss of water transparency, threaten aquatic organisms, and signal ineffective wastewater treatment. Such monitoring will allow environmental safety control and blockage prevention in treatment systems as well as meeting the limits of TSS measurement of ≤ 10 mg/L for unrestricted urban use and ≤ 30 mg/L for discharge into surface water defined by ISO 30500 (BS ISO 30500:2018, 2018). In this study, the TSS concentrations of the raw liquid input spanned over a wide range, 3140–2240 mg/L, while for the scrubber liquid the values were significantly lower, always below 140 mg/L. However, the TSS concentration was not consistently achieved below the recommended level for discharge into surface water (i.e. ≤ 30 mg/L). Only on 'Day 1' the concentration achieved a value of less than 10 mg/L.

Figure 4-15 shows the Carbon Oxygen Demand (COD) in both the raw input and scrubber liquid over a five-day period, demonstrating the variations in organic matter concentration during this time.

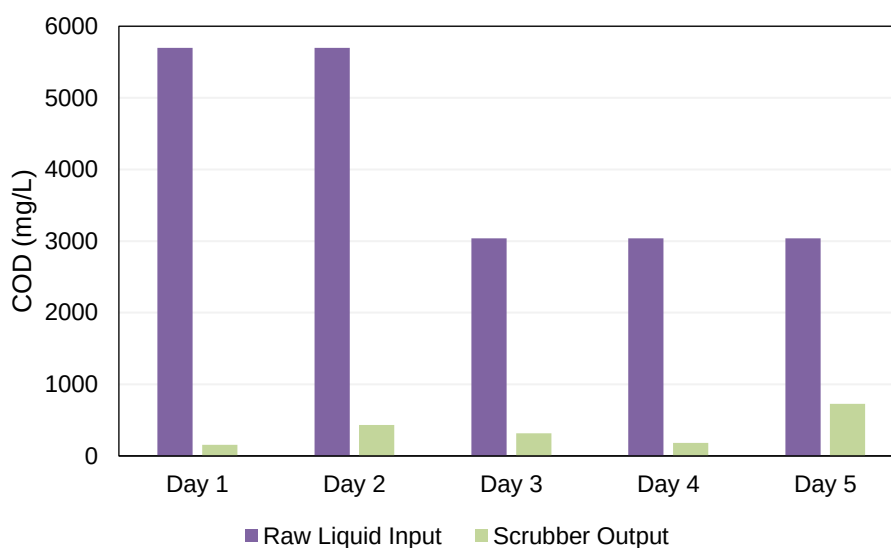


Figure 4-15 Carbon oxygen demand (COD) in raw input and scrubber liquid over a five-day period

COD is a representative metric denoting the volume of oxygen consumed for the oxidation of dissolved organic and particulate matter in water, measured in mg O₂/L. It is used as an approximate measure for the concentration of organic content, with higher COD indicating a higher concentration of organic pollutants. Monitoring COD concentration in water is essential because the excessive amount of organic matter can be decomposed, consuming available oxygen, which can disrupt the aquatic ecosystem. ISO 30500 set concentrations of ≤50 mg COD/L in effluent as the limit for unrestricted urban applications of such water. Moreover, COD ≤ 150 mg/L is the maximum limit for discharge into surface water and other restricted urban use (BS ISO 30500:2018, 2018). In this study COD value of raw input was between 3040-5700 mg/L, whereas COD content in the scrubber liquid ranged between 156-728 mg/L.

Figure 4-16 illustrates the pH values in the raw input, and scrubber liquid over a five-day period.

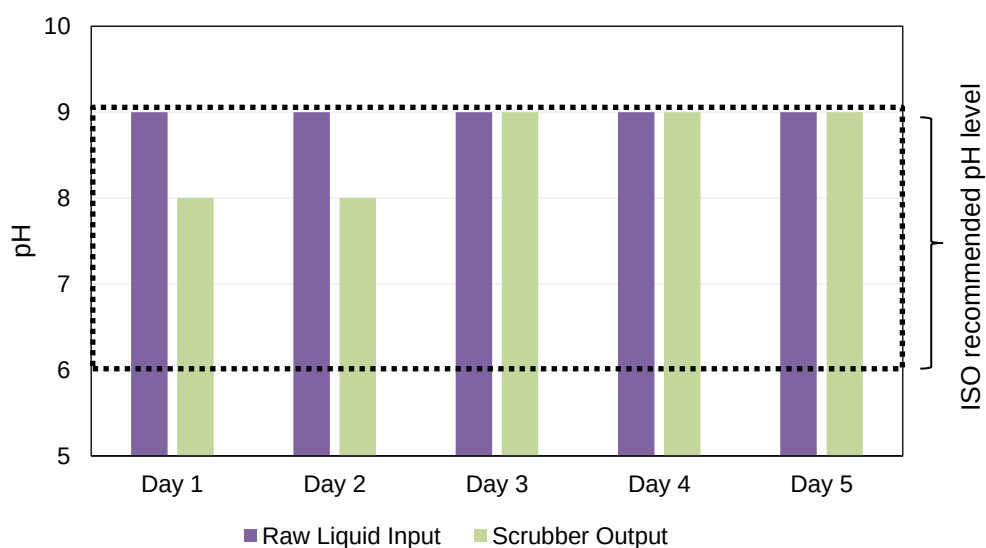


Figure 4-16 pH value in raw input, and scrubber liquid over a five-day period

Raw liquid input's pH was always equal to 9 and the scrubber liquid maintained a pH range of 8 to 9 (Figure 4-16). According to ISO 30500, an acceptable effluent pH for all reuse purposes ranges between 6 to 9, ensuring safe and acceptable limits for discharge and reuse.

Figure 4-17 shows the electrical conductivity (EC) in both the raw input and scrubber liquid over a five-day period.

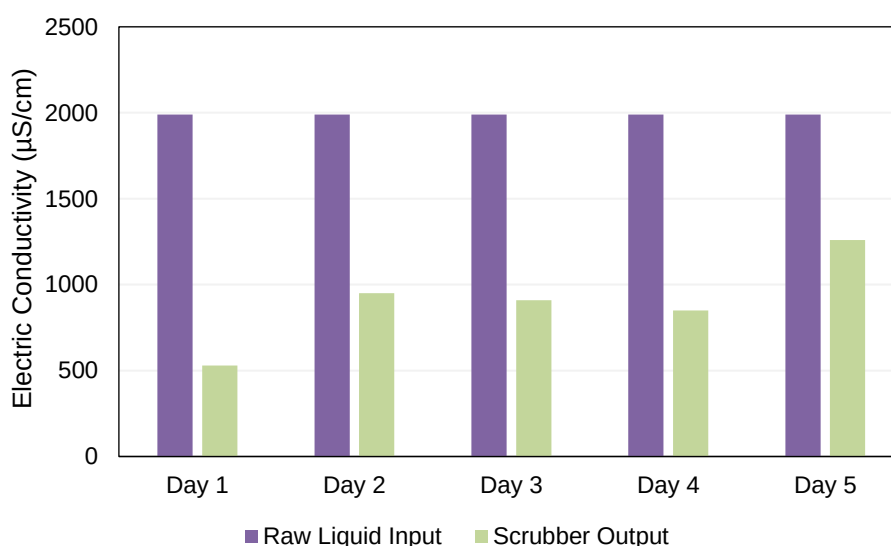


Figure 4-17 Electric conductivity (EC) in raw input and scrubber liquid over a five-day period

High electric conductivity values ($>1990\ \mu\text{S}/\text{cm}$) in the raw liquid input achieved only into small reductions in the scrubber-treated effluent ($530\text{--}1350\ \mu\text{S}/\text{cm}$). Liquid effluent has no required values for EC in ISO 30500. However, in this study, we measured EC because it reflected the dissolved ions concentrations and provided an indication of salts and other conductive species in the liquid.

4.2.3 Liquid Evaporation Rate of the System

The system's liquid evaporation rate was measured to determine its liquid processing capacity. The ultimate objective was to develop a closed-loop system with zero liquid discharge, where all liquid was processed and evaporated with no remaining waste.

Table 4-9 Liquid evaporation rate over five days

Date	Liquid Evaporation Rate (mL/hr)
Day 1	42.7
Day 2	40.0
Day 3	35.3
Day 4	57.3
Day 5	56.9

The minimum liquid evaporation rate was recorded at $35.3\ \text{mL/hr}$, while the highest was $56.9\ \text{mL/hr}$ (Table 4-9). The average evaporation rate of $46.4\ \text{mL/hr}$ is considered optimal and can be further increased by adjusting the temperature (TF2) parameters. Figure 4-18 displays the liquid evaporation rate over a period of five days

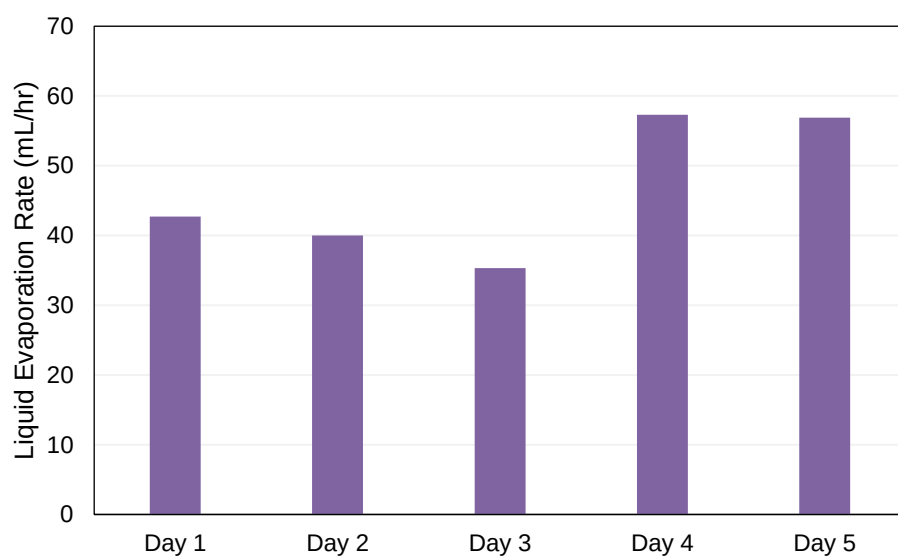


Figure 4-18 Liquid evaporation rate over five days

4.3 Rheological Analysis of Char: Properties and Trends

A comprehensive char rheology chart was developed using char samples systematically collected throughout the testing period (Table 4-10).

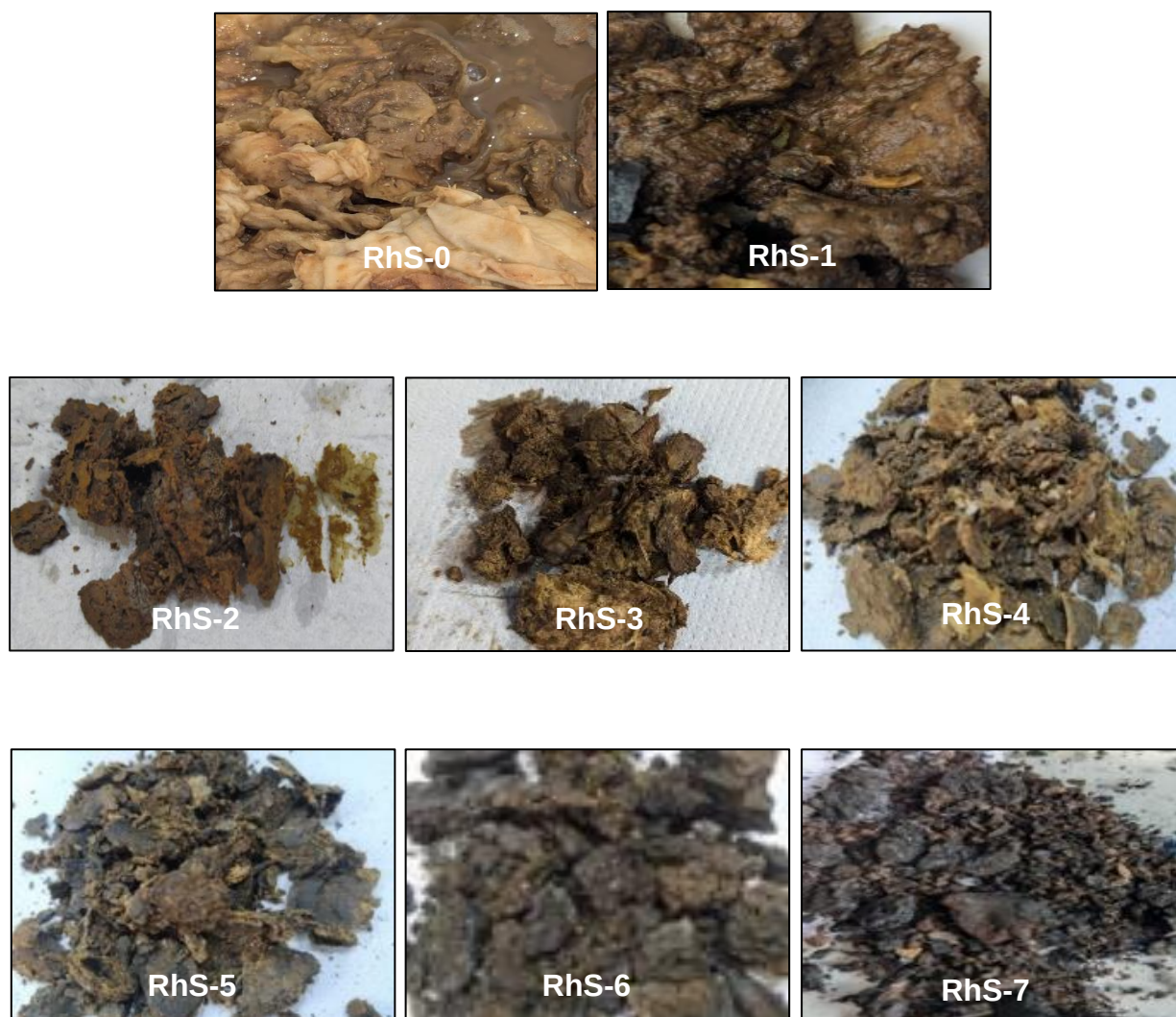


Figure 4-19 Char rheology states at different torrefaction conditions, ranging from rheology state 0 to rheology state 7

Table 4-10: Char rheology chart

	Physical Properties				Chemical Properties									Biological Properties		Image
	Colour	Hydrophobicity	Moist/Dry	Texture	Proximate Analysis (wt. %)				Ultimate Analysis (wt. %, dry basis)					E.coli (MPN/g dry solids)	C.perfringens (CFU/g dry solids)	
					Moisture %	Volatile%	Fixed Carbon%	Ash%	N%	C%	H%	S%	O%			
RhS-0	Light brown/Brown	Hydrophilic	Moist	Raw	80	17	2	1	2.0±0.1	48.1±0.2	7.2±0.0	0.1±0.0	42.3±0.3	>24200	>1000	
RhS-1	Light brown/Brown	Hydrophilic	Moist	Wet with very high surface tension	73	24	2	1	1.7±0.0	49.3±0.0	8.5±0.1	0.1±0.0	40.2±0.2	580	40	
RhS-2	Light brown/Brown	Hydrophilic	Moist	Slippy with high surface tension	54	29	7	11	3.7±0.0	45.7±0.2	7.6±0.1	0.5±0.0	42.2±0.3	<10	<10	
RhS-3	Brown	Hydrophilic	Moist	Sticky with low surface tension	7	76	9	8	1.2±0.0	44.9±1.2	7.6±0.2	0.1±0.0	46.0±1.4	<10	<10	
RhS-4	Brown	Hydrophilic	Moist	Low adhesion	6	72	13	8	2.0±0.1	51.3±0.1	8.2±0.1	0.1±0.0	38.2±0.2	<10	<10	
RhS-5	Brown/Black	Hydrophobic	Dry	Rubbery	3	70	15	12	5.2±0.2	51.9±0.2	8.5±0.1	0.3±0.0	33.8±0.6	<10	<10	
RhS-6	Brown/Black	Hydrophobic	Dry	Brittle	2	70	15	14	5.2±0.1	53.1±0.5	8.7±0.3	0.4±0.0	32.3±0.7	<10	<10	
RhS-7	Black	Hydrophobic	Dry	Brittle	1	60	22	17	5.2±0.3	59.1±3.9	6.9±1.0	0.2±0.0	28.3±4.5	<10	<10	

Eight distinct rheological states (RhS-0 to RhS-7) were identified from the char samples collected during the testing period (Figure 4-19). The physical properties characterized for each state included colour, hydrophobicity, moisture content, and surface characteristics. The colour progressed from light brown/brown to black, while the hydrophobicity showed a transition from hydrophilic (RhS-0 to RhS-4) to hydrophobic (RhS-5 to RhS-7) behaviour. The moisture content ranged from wet/liquid in the initial states to dry in the final states. Surface properties varied across the states, exhibiting characteristics from high surface tension to granular and brittle textures, as shown in Table 4-10.

Figure 4-20 shows the rheological states of solid output, classified by colour and appearance, highlighting the visual differences across various states.

Light brown-Brown			Brown		Brown-Black		Black
RhS-0	RhS-1	RhS-2	RhS-3	RhS-4	RhS-5	RhS-6	RhS-7
							
Raw	Wet with very high surface tension	Slippy with high surface tension	Sticky with low surface tension	Low adhesion	Rubbery	Brittle	Brittle

Figure 4-20 Rheological states of solid output: classification by colour and appearance

As torrefaction progresses, the biomass undergoes significant chemical transformations, which are reflected in noticeable colour changes. The conversion process leads to the formation of hydrosols, carbonyls, methoxyls, and phenolic compounds, all of which contribute to the shift in colour (Patidar & Vashishtha, 2020). Char produced at lower torrefaction temperatures (200 to 225

°C) appears light brown, while moderate torrefaction (250 to 275 °C) results in dark brown, and severe torrefaction (300 °C) produces black char (Khairy et al., 2024). This conclusion aligned with research findings showing a progressive colour change from yellow to brown, then to dark brown, and finally to black, corresponding to rheology states ranging from 0 to 7 (Figure 4-20).

Figure 4-21 depicts the rheological states of solid output, classified by hydrophobicity.

Hydrophilic					Hydrophobic		
RhS-0	RhS-1	RhS-2	RhS-3	RhS-4	RhS-5	RhS-6	RhS-7

Figure 4-21 Rheological states of solid output: classification by hydrophobicity

The hydrophobicity of torrefied biochar was assessed by immersing the samples in water for a duration of 15 hours to observe their water solubility (Tumuluru, et al., 2011). A study on dry torrefied sewage sludge found that its hydrophobic properties increased with higher torrefaction temperatures and longer durations (Białowiec et al., 2020).. This phenomenon is attributed to the decreasing O/C and H/C molar ratios, which result from the rising concentrations of long-chain and aromatic compounds. These compounds are less prone to degassing than other carbohydrates, leading to reduced polarity and lower water affinity (Białowiec et al., 2020).In this rheology chart, hydrophobicity is observable in rheology states 5 to 7.

Figure 4-22 illustrates the rheological states of solid output, classified by moisture content and dry appearance, highlighting the variations in texture and consistency across different states.

Moist					Dry		
RhS-0	RhS-1	RhS-2	RhS-3	RhS-4	RhS-5	RhS-6	RhS-7

Figure 4-22 Rheological states of solid output: classification by moisture/dry appearance

The rheology chart shows a clear characteristic transition in moisture content, with rheology states 0 to 4 having a high moisture content, while rheology states 5 to 7 have decreasing moisture levels because of the deep drying nature of torrefaction. Torrefaction significantly reduced the moisture content of pre-dried biomass, as observed in previous studies where biomass dried from 10% moisture content was subjected to temperatures up to 300°C for more than 30 minutes (Sadaka & Negi, 2009). Similar findings were reported in studies on wheat straw, rice straw, and cotton gin waste, where moisture content was reduced by 70.5%, 49.4%, and 48.6%, respectively, under extreme torrefaction conditions (315°C for 180 minutes) (Sadaka & Negi, 2009).

Table 4-11 presents the pathogen levels (*E. coli* and *C. perfringens*) for each rheological state, providing an overview of microbial contamination across different states.

Table 4-11 Pathogen level (*E.coli* and *C.perfringens*) for each rheology state

Rheology State	<i>E. coli</i> (MPN/g dry solids)	<i>C. perfringens</i> (CFU/g dry solids)
RhS-0	>24200	>1000
RhS-1	580	40
RhS-2	<10	<10
RhS-3	<10	<10
RhS-4	<10	<10
RhS-5	<10	<10
RhS-6	<10	<10
RhS-7	<10	<10

Wet and moist chars (RhS-0 to RhS-2) exhibited higher microbial presence, whereas significantly drier, high-temperature-treated chars (RhS-3 to RhS-7) showed a notable decline in microbial counts.

In the microbial analysis, *E. coli* and *C. perfringens* reached less than 10 from rheology state 2, which qualifies ISO 30500 sanitation standard. These findings held significant implications in confirming that torrefaction could effectively inactivate the pathogens yet indicate the importance of optimising torrefaction

parameters to ensure that desirable char properties can be maintained for reuse in sustainable applications (Tumuluru, et al., 2011).

Figure 4-23 shows the percentage distribution of moisture, volatile matter, ash, and fixed carbon content across different rheological states (RhS-0 to RhS-7)

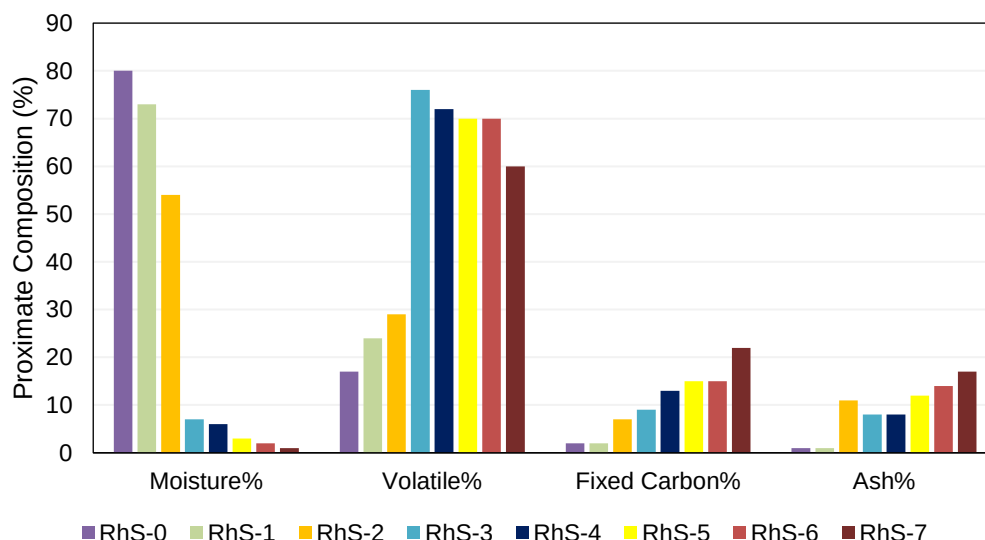


Figure 4-23 Percentage of moisture, volatile matter, ash, and fixed carbon content across different rheological states (RhS-0 to RhS-7)

The moisture content showed a clear decreasing trend from RhS-0 to RhS-7, with values going from a maximum of 80% in RhS-0 to a minimum of 1% in RhS-7. On the contrary, volatile matter followed a different trend, first increasing from 17% at RhS-0 to a peak of 76% at RhS-3 and slightly decreasing to 60% at RhS-7. Previous studies have confirmed that at higher torrefaction temperatures, the thermal decomposition of complex polymers leads to an increase in fixed carbon and ash content while simultaneously decreasing the amount of volatile matter (Khairy et al., 2024). Fixed carbon content displayed a generally increasing trend from RhS-0 (2%) to RhS-7 (22%), with some fluctuations in the middle stages. The increase in fixed carbon in thermally treated samples occurred due to the carbonization of carbohydrates during torrefaction (Khairy et al., 2024). The Ash content was different between the samples, ranging from 1% for RhS-0 to the highest numbers for RhS-6 (14%) and RhS-7 (17%), with the intermediate stages showing variation.

Figure 4-24 illustrates the percentage distribution of elements across different rheological states (RhS-0 to RhS-7), providing insights into how element composition varies with each rheological state.

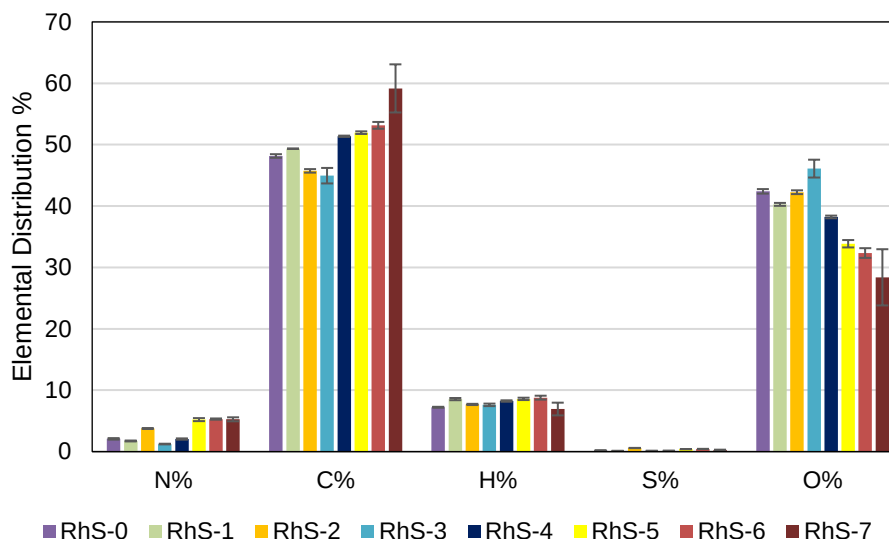


Figure 4-24 Percentage distribution of elements across different rheological states (RhS-0 to RhS-7)

Each rheology state followed a similar pattern, with high carbon, followed by oxygen, then lower hydrogen and nitrogen content, while sulphur content was very low.

Concerning carbon (C%), there was a remarkable increasing trend observed between RhS-0 and RhS-7, with the maximum content (59.163%) detected in RhS-7. Interestingly, at RhS-2 and RhS-3, a variation in carbon content was observed. Oxygen (O%) had an inverse relationship with carbon, increasing to RhS-4 and then dropping significantly at RhS-7. The maximum value of oxygen content (46.097%) was found in RhS-4, while the minimum value (28.389%) occurred in RhS-7. H% across all rheology states was consistent (6-9%). In the same way, nitrogen (N%) varied slightly but remained less than 5%. Sulphur (S%) was measured in small quantities in all the rheology states and was near zero.

Beaton et al., (2004) investigated the torrefaction of miscanthus and reported similar findings, observing that increasing the temperature to 280°C and extending the duration to 2 hours led to a rise in carbon content (from 43.5% to

52%) while reducing hydrogen (6.49% to 5.54%), nitrogen (0.90% to 0.65%), and oxygen levels. In torrefaction studies of reed canary grass and wheat straw, increasing operation temperature from 230, 250, 270, to 290°C for 30-minute residence times led to carbon increase from 48.6% to 54.3%, and hydrogen and nitrogen content decrease from 6.8% to 6.1% and from 0.3% to 0.1%, respectively (Bridgeman et al., 2008).

This comprehensive rheology chart, which details the physical, chemical, and biological properties across distinct char states, serves as a standardised reference for agricultural and environmental applications. It enables researchers and practitioners to select the most appropriate char type based on key parameters such as moisture content, hydrophobicity, nutrients' composition, and pathogen safety. By using this rheological classification, both research and applied fields can be optimised for soil amendment and carbon sequestration sustainably with crop production. This chart, a rather remarkable contribution to human solid waste management and valorisation, is applied as a practical, reliable guide for the safe and effective reuse of char products. It bridges the gap between carefully controlled, laboratory-scale torrefaction studies and actual applications in agriculture, sanitation, and environmental restoration. Most importantly, it would not require future researchers to repeat detailed characterisations for every char sample. It would allow them to quickly identify and use the char type best suited to their application. Thus, it promotes streamlined experimentation and implementation while opening new avenues of research in biochar-soil interactions, nutrient cycling, and long-term field performance- through innovative waste-to-resource solutions furthering circular economy strategies.

5 Conclusion

This study investigates the impact of temperature and rotation speed on the torrefaction process, pathogen elimination, and the physical, chemical, and biological characteristics of char output, while also developing a char rheology chart based on the collected data.

Higher temperatures (around 200°C) successfully removed microbial contamination in the output biochar, with *E. coli* and *C. perfringens* concentrations below 10 MPN/g and 10 CFU/g, respectively. At a lower temperature (150°C), increasing retention time by lowering rotation speed from 0.22 to 0.11 RPM reduced *C. perfringens* levels from 30 to 20 CFU/g. Increasing the temperature from 150°C to 200°C reduced the moisture level in the biochar from 14% to 3%, regardless of the rotation speed. While volatile matter content remained reasonably consistent across processing conditions (69-85%), carbon retention increased with higher operation temperatures and longer retention durations. The maximum carbon concentration (50.44%) was detected at 200°C and 0.11 RPM. Treatment at 250°C with 0.083 RPM resulted in a biochar with excellent torrefied properties, including low moisture content (5%), increased hydrophobicity, improved grindability, and significant pathogen removal, with *E. coli* levels reduced to <10 MPN/g.

Furthermore, a novel rheology classification system (RhS-0 to RhS-7) was developed to describe the progressive transformation of torrefied char. Transitioning from RhS-0 to RhS-7 resulted in colour shift from yellow/brown to black, increased hydrophobicity, and reduced moisture content (from 80% at RhS-0 to 1% at RhS-7). Across this transformation, volatile matter increased from 17% to 60%, fixed carbon content rose from 2% to 22%, and ash content varied from 1% to 17%. Elemental analysis showed a progressive change from RhS-0 to RhS-7, with carbon as the most abundant component increasing from 48% to 59%, followed by a decrease in oxygen from 42% to 27% and hydrogen from 6% to 9%. Nitrogen levels varied from 2% to 5%, while sulphur remained at very low levels (0.16–0.4%). The rheology chart will help researchers better understand the transformation of biochar during torrefaction. These findings offer valuable

insights for optimising biochar production parameters to achieve superior quality for agricultural and environmental applications. Future work could involve varying input feed characteristics, such as moisture content and composition, and analysing their effects on outputs such as char quality. This would provide deeper insights into system robustness and process optimization. Additionally, assessing the applicability of the torrefaction process in real sanitation environments and evaluating the long-term performance of the produced biochar in practical applications could help translate these laboratory findings into scalable solutions.

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Appendices

Appendix A Ethical Approval Letter



10 May 2024

Dear Mrs Daundasekara ,

Reference: CURES/22008/2024

Project ID: 25100

Title: Optimization of the Solid Treatment Module to Manage (Solid, Liquid, Gas) Output-in Compliance with the ISO 30500

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/22008/2024 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Parameters Used in Research

Table B-1 Parameters Used in Testing the Impact of Torrefaction Parameter Variations on Char Properties (BS ISO 30500:2018, 2018)

Parameters	Test 1	Test 2	Test 3	Test 4
Air pumps speed %	40	40	40	40
Air pumps on time (sec)	600	600	600	600
Air pumps off time (sec)	300	300	300	300
Air pumps on temperature (°C)	250	250	250	250
Air pumps off temperature (°C)	300	300	300	300
Liquid pump speed %	20	20	20	20
TF1 motor minimum rotation temperature (°C)	100	100	100	100
TF1 motor maximum rotation temperature (°C)	700	700	700	700
TF1 motor minimum temperature (°C)	140	140	190	190
TF1 motor target temperature (°C)	150	150	200	200
TF1 motor maximum temperature (°C)	160	160	210	210
TF1 motor shutdown temperature (°C)	300	300	300	300
TF1 motor speed %	100	100	100	100
TF1 motor rotation direction	CW*	CW*	CW*	CW*
TF1 motor rotation angle (°)	120	120	120	120
TF1 motor rotation time (sec)	180	90	180	90
Tf2 motor speed %	100	100	100	100
Tf2 motor rotation direction	CW	CW	CW	CW
TF2 (heat tape) temperature (°C)	110	110	110	110
TF2 motor rotation angle (°)	360	360	360	360
TF2 motor rotation time (sec)	10	10	10	10
Fan speed %	50	50	50	50
Fan turn-on time (sec)	6000	6000	6000	6000
Fan turn off time (sec)	6	6	6	6
Fan turn on temperature (°C)	30	30	30	30
Fan turn off temperature (°C)	80	80	80	80

*CW: Clockwise

Table B-2 Parameters Used in System Performance Evaluation Under Continuous Operation (Five-Day Testing) (BS ISO 30500:2018, 2018)

Parameters	Value
Air pumps speed %	40
Air pumps on time (sec)	600
Air pumps off time (sec)	300
Air pumps on temperature (°C)	250
Air pumps off temperature (°C)	300
Liquid pump speed %	20
TF1 motor minimum rotation temperature (°C)	100
TF1 motor maximum rotation temperature (°C)	700
TF1 motor minimum temperature (°C)	240
TF1 motor target temperature (°C)	250
TF1 motor maximum temperature (°C)	260
TF1 motor shutdown temperature (°C)	300
TF1 motor speed %	100
TF1 motor rotation direction	CW*
TF1 motor rotation angle (°)	30
TF1 motor rotation time (sec)	80
Tf2 motor speed %	50
Tf2 motor rotation direction	CW*
TF2 (heat tape) temperature (°C)	200
TF2 motor rotation angle (°)	360
TF2 motor rotation time (sec)	10
Fan speed %	50
Fan turn-on time (sec)	600
Fan turn off time (sec)	6
Fan turn on temperature (°C)	30
Fan turn off temperature (°C)	800

*CW: Clockwise

Appendix C Solid Output and Effluent ISO 30500 Requirements

C.1 Solid Output Requirements

Table C-3 Solid Output Validation Thresholds and Log Reduction Values (LRVs) for Human Health Protection (BS ISO 30500:2018, 2018)

Parameter (Pathogen Class)	Human Enteric Bacterial Pathogens	Human Enteric Protozoa
Surrogate	Using <i>E. coli</i> as surrogate, measured in CFU or MNP	Using viable <i>Clostridium perfringens</i> spores as surrogate, measured in CFU
Max. concentration in solids [number/g (dry solids)]	100	< 1
Overall LRV for solids	≥ 6	≥ 6

(a) Log-reduction values (LRVs) were derived from a quantitative microbial risk assessment (QMRA) as described by WHO 2016, assuming 1 g of fecal solids contains approximately the same range of reference pathogens as in 1 L of liquid effluent.

(b) *E. coli* strain K011 (ATCC 55124) is selected because it is nalidixic acid-resistant. Therefore, this antibiotic may be added to the plating medium to suppress the growth of other interfering bacteria.

C.2 Liquid Output Requirements

Table C-4 Effluent Performance Thresholds for Environmental Parameters

(BS ISO 30500:2018, 2018)

Usage Category	COD (mg/l)	TSS (mg/l)
Category A usage: Threshold for unrestricted urban uses	≤ 50	≤ 10
Category B usage: Threshold for discharge into surface water or other restricted urban uses	≤ 150	≤ 30

- Category A usage refers to unrestricted urban uses that comprise all uses where public access is not restricted (e.g., landscape irrigation, toilet flushing).
- Category B usage refers to discharge into surface water and other restricted urban uses that comprise all uses where public access is controlled or restricted by physical or institutional barriers (e.g., fences, temporal access restriction).
- COD refers to total COD unfiltered.

Table C-5 Effluent Performance Load Reduction Percentage for Nutrients (Environmental Requirement) (BS ISO 30500:2018, 2018)

Parameter	Minimum Load Reduction Percentage (%)
Total Nitrogen (TN)	70
Total Phosphorus (TP)	80

Table C-5 Effluent Performance Range for pH (Environmental Requirement) (BS ISO 30500:2018, 2018)

Parameter	Range For All Reuse Purposes
pH	6 to 9

