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Techno-economic assessment of polyurethane flexible foam waste-to-energy via incineration - a Kenyan case study.

Mzee, Shake Francis
School of Computing and Engineering Sciences
Strathmore University

Techno-Economic Assessment of Polyurethane Flexible Foam Waste-To-Energy via Incineration: A Kenyan Case Study

Francis Shake Mzee

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Declaration

I declare that this dissertation is my original work and has not been submitted to any learning institution for the attainment of my degree. The dissertation ensures that all the information sources cited here have been fully acknowledged.

Francis Shake Mzee

23rd May 2025

Approval

The dissertation of Francis Shake Mzee was reviewed and approved by the following:

Dr.Eng. Fenwicks S. Musonye., P.E., CEM®., CMVP®., CREP®., PMP®
Adjunct Faculty Member
School of Computing and Engineering Sciences
Strathmore University

Dr. Julius Butime
Dean, School of Computing and Engineering Sciences,
Strathmore University

Prof. Benard Shibwabo
Director of Graduate Studies,
Strathmore University

Abstract

In response to escalating waste management challenges and growing energy demands, this study evaluates the technical and economic feasibility of recovering energy from post-consumer flexible polyurethane (PU) foam waste in Kenya via advanced incineration technologies. Employing empirical data analysis, thermochemical modelling, and economic assessment, the research first estimates Kenya's annual PU foam waste generation—projected at 18,909.20 tonnes in 2025, with 9,545.60 tonnes deemed collectable—and determines a net calorific value of 23.131 MJ/kg, corresponding to an energy potential of 218.7 million MJ for collectable waste. Comparative analysis demonstrates that a fluidized bed incinerator yields 167.3 million MJ of thermal energy and 13,825.58 MWh of electricity, outperforming a mass burn incinerator's 13.94 million MJ and 9,294.51 MWh, while Levelized Cost of Electricity (LCOE) calculations indicate marginal cost differences of USD 0.22 /kWh versus USD 0.23 /kWh, respectively. The findings offer critical insights into waste generation patterns, energy recovery efficiencies, and financial viability and support recommendations for refining waste estimation models, conducting experimental energy-content analyses, and establishing pilot-scale facilities to advance sustainable waste-to-energy solutions.

Keywords:

Post-consumer polyurethane foam waste; Fluidized bed incineration; Mass burn incineration; Energy recovery potential; Levelized Cost of Electricity; Techno-economic assessment

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Chapter 1: Introduction

1.1 Contextual Background

The end-of-life waste management of PU foam products presents technical challenges regarding energy management (Hoornweg & Bhada-Tata, 2012; Malinauskaite et al., 2017). Energy recovery through incineration has diverse implications for energy use and recovery (Iram et al., 2022). Finding the balance between the advantages of reducing waste and energy recovery requires careful evaluation (Ghisellini, Cialani, & Ulgiati, 2016). Reducing, reusing, and recycling post-consumer waste materials has emerged as a pivotal strategy for mitigating environmental impact and fostering sustainable development (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). Polyurethane (PU) foam waste, originating from a range of products such as mattresses, presents a particularly pressing issue due to its ubiquity and potential environmental ramifications (Grand View Research, 2022).

Waste management through reduction, reusing, recycling, and energy conservation have become necessary measures (Arena, Di Gregorio, & Santonastaso, 2015). Although methods like incineration show potential for diverting and reducing waste, the energy implications of incineration need careful examination (Sharypov, Gomez, Muñoz, & Sidorenko, 2022). While the environmental advantages of waste reduction are widely recognized, their actual impact is still to be fully demonstrated (Sadhwani, Kumar, & Rodriguez, 2020).

As such, this study analyses the feasibility of energy recovery by incinerating PU foam waste. Kenya has no dedicated waste management solution explicitly targeting PU foam waste products (KEPRO, 2021). Additionally, this study seeks to identify the energy considerations embedded within the incineration process of post-consumer PU foam waste, explicitly focusing on the Kenyan context. The main goal is to establish a model that quantifies post-consumer waste generation, delves into the incineration process of these waste materials as feedstock, and evaluates the associated energy implications.

1.2 Problem Statement

Waste-to-energy solutions offer a promising solution for addressing waste management challenges while harnessing renewable energy sources. In Kenya, as in many other regions, the characterization and analysis of feedstocks present a hurdle in effectively implementing such solutions. Polyurethane (P.U.) foam waste stands out as one of the viable feedstocks for waste-to-heat conversion.

However, a gap exists in understanding the energy recovery potential from post-consumer flexible foam waste within the Kenyan market. This lack of insight hinders the development of tailored waste-to-energy strategies that could unlock the latent energy value of P.U. foam waste. Moreover, while thermal energy recovery through incineration presents a feasible solution, the feasibility of further converting this thermal energy into electrical energy remains largely unexplored. Thus, a comprehensive analysis of the energy recovery potential from post-consumer flexible foam waste and assessing the feasibility of converting thermal energy to electrical energy is imperative to inform sustainable waste management practices and advance Kenya's renewable energy objectives.

This study seeks to address these challenges by investigating the viability and feasibility of energy recovery by incineration of post-consumer flexible foam waste in the Kenyan context. The primary focus is determining whether incineration can provide a sustainable solution for managing waste, reducing environmental impact, and minimizing material accumulation.

1.3 Objectives of the Study

1.3.1 General Objective:

This study evaluates incineration's viability as a waste management solution for reducing post-consumer flexible foam waste.

1.3.2 Specific Objectives:

i) To estimate the rate of post-consumer flexible P.U. foam waste generation in Kenya.

ii) Analyze the energy content of post-consumer flexible P.U. foam waste collected from diverse regions in Kenya.

iii) Evaluate the thermal and electrical energy potential of post-consumer flexible P.U. foam waste.

iv) Determine the Levelized Cost of Electricity (LCOE) associated with the incineration-based energy recovery process of the post-consumer flexible polyurethane foam waste.

1.3.3 Research Questions

i) What is the current and projected rate of post-consumer flexible P.U. foam waste generation in Kenya based on raw material imports, production volumes, and product lifecycles?

ii) What are the characteristic energy content values of post-consumer flexible P.U. foam waste collected from different regions in Kenya? How do variables such as foam density, age, and condition affect the energy content of the waste materials?

iii) What is the theoretical maximum thermal and electrical energy potential from the identified post-consumer flexible P.U. foam waste volumes in Kenya, and how do conversion efficiencies affect the practical energy recovery potential from the waste materials?

iv) What is the expected LCOE for energy recovery from post-consumer flexible P.U. foam waste incineration in Kenya, and how do capital costs, operating costs, and electricity generation potentially influence the economic viability of the process?

1.4 Research Justification

According to Hoornweg & Bhada-Tata (2012), waste management is one of the major global concerns, with the rapid growth of populations, urbanization, and consumption patterns leading to increased waste generation. The improper disposal of waste, particularly in developing countries, has environmental, social, and economic consequences, including greenhouse gas emissions, air and water pollution, and public health risks (Kaza et al., 2018).

As a result, there is a need for sustainable waste management solutions that align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 7 (Affordable and Clean Energy) and SDG 15 (Life on Land) (United Nations, 2015). As a waste-to-energy process, incineration has emerged as a plausible solution to address waste management challenges while simultaneously contributing to achieving the SDGs.

By converting waste into energy, incineration reduces waste sent to landfills, addresses greenhouse gas emissions, and generates clean and affordable energy (Beyene et al., 2018). This process is relevant for post-consumer flexible polyurethane (P.U.) foam waste, which is a concern due to its widespread use in comfort applications, such as mattresses and upholstered furniture, and its limited recycling options (Gómez-Rojo et al., 2019).

In the context of Kenya, the management of post-consumer P.U. foam waste is a concern, as the country experiences rapid population growth, urbanization, and a growing middle class, leading to increased consumption of P.U. foam products (Oyake-Ombis et al., 2015). Kenya's current waste management infrastructure is inadequate, with most waste being disposed of in open dumps or landfills, resulting in environmental degradation and public health risks (Njoroge et al., 2014).

The Kenyan government has introduced various legislative and policy frameworks to address these challenges, such as the Environmental Management and Coordination Act (EMCA) and the National Solid Waste Management Strategy (Ministry of Environment and Forestry, 2019). The EMCA, enforced by the National Environment Management Authority (NEMA), provides legal guidance for sustainable waste management in Kenya (NEMA, 2012). The Act emphasizes the importance of waste minimization, resource recovery, and the adoption of cleaner production technologies. Additionally, the Kenya Extended Producer Responsibility Organization (KEPRO) has been established to promote the implementation of extended producer responsibility (EPR) schemes, which aim to enhance waste collection, recycling, and recovery (KEPRO, 2021).

Despite these initiatives, there is still a lack of specific policies and strategies targeting the management of post-consumer P.U. foam waste in Kenya. This highlights the need for research to explore viable solutions, such as energy recovery through incineration, providing valuable insights and recommendations for policymakers, industry stakeholders, and waste management practitioners.

1.5 Research Scope

This study aims to evaluate the techno-economic feasibility of energy recovery via the incineration of post-consumer flexible polyurethane (P.U.) foam waste in Kenya. The scope of the study encompasses the following key aspects:

1.5.1 Geographical Scope

The Study focuses on Kenya, a country in East Africa, as a representative case for the region. Kenya has been selected due to its rapidly growing population, urbanization, and increasing consumption of P.U. foam products. (Oyake-Ombis et al., 2015).

1.5.2 Waste Stream

The Study specifically targets post-consumer flexible P.U. foam waste primarily generated from comfort applications, such as mattresses and upholstered furniture. This waste stream has been chosen due to its significant volume, limited recycling options, and potential for energy recovery (Gómez-Rojo et al., 2019).

1.5.3 Waste-to-Energy Technology

The Study focuses on incineration as the primary technology for converting post-consumer P.U. foam waste to energy. Incineration has been selected due to its proven track record in reducing waste volume, generating clean energy, and mitigating greenhouse gas emissions (Beyene et al., 2018).

1.5.4 Techno-Economic Assessment

The Study conducts a comprehensive techno-economic evaluation of P.U. foam waste incineration, including the Estimation of waste generation rates, analysis of energy content, evaluation of thermal and electrical energy potential, and determination of the levelized cost of electricity (LCOE). LCOE was deemed most suitable because it provides a standardized, unit-based cost measure (USD/kWh), which enables straightforward comparison across different energy technologies and project configurations, independent of scale, financing structure, or location.

This study did not employ alternative financial appraisal methods, such as Net Present Value (NPV) and Internal Rate of Return (IRR) for several reasons. First, NPV and IRR require detailed cash flow projections, discount rates, and assumptions about project-specific financing, which are often unavailable or highly uncertain at early-stage feasibility levels—especially in developing contexts like Kenya (Short et al., 1995). Secondly, IRR can be misleading for projects with non-standard cash flows, and NPV is sensitive to the choice of discount rate, making cross-technology comparisons more complex. This assessment will provide insights into the proposed waste-to-energy solution's technical feasibility and economic viability (Towler & Sinnott, 2013).

1.6 Limitations of the Study

While this research aims to establish a comprehensive techno-economic feasibility assessment of energy recovery from post-consumer flexible polyurethane (P.U.) foam waste in Kenya, certain limitations may influence its findings' scope, depth, and generalizability. These limitations, rooted in the Kenyan context, must be considered to provide a balanced understanding of the study's outcomes and potential application.

One key limitation lies in the challenges associated with accessing reliable data. The research relies primarily on secondary data sources such as industry publications, government reports, and academic literature. However, information on P.U. foam waste generation, characteristics, and management practices in Kenya may be sparse, outdated, or inconsistent. For instance, Oyake-Ombis et al. (2015) highlight the fragmented nature of data collection in Kenya's waste management sector, which can lead to significant uncertainties. These data gaps may hinder accurate estimations of critical parameters, such as waste quantities and energy content, potentially affecting the overall accuracy of the techno-economic assessment. Without robust, locally-sourced data, the findings may lack the precision necessary to confidently inform policy or investment decisions.

Another limitation concerns the generalizability of the study's findings. The research focuses exclusively on post-consumer flexible P.U. foam waste within the Kenyan context, which may restrict the applicability of its conclusions to other waste streams, technologies, or geographical regions. Kenya's waste management system, energy market dynamics, and socio-economic conditions present unique characteristics that influence the feasibility and sustainability of energy recovery technologies. As a result, the recommendations derived from this study may not translate effectively to countries with different waste compositions, economic priorities, or regulatory frameworks. For instance, a country with advanced waste segregation systems or lower energy costs might find the study's conclusions less relevant.

The study will employ a transparent and rigorous methodology to address the limitations, clearly stating the assumptions, uncertainties, and potential biases in the analysis. The study will also provide recommendations for future research and data collection efforts to bridge the identified knowledge gaps and support the development of evidence-based policies and strategies for sustainable P.U. foam waste management in Kenya.

1.7 Beneficiaries of the Study

The research findings and benefits will be systematically distributed across multiple stakeholder groups through various channels and mechanisms. The study's outcomes will directly inform policymakers in Kenya's waste management sector by providing empirical evidence on the technical and economic viability of energy recovery from flexible polyurethane foam waste through incineration. This knowledge will support evidence-based decision-making regarding waste-to-energy infrastructure investments and policy formulation. County and national government entities, particularly those responsible for environmental management and energy policy, will gain access to locally contextualized data essential for developing integrated waste management strategies and renewable energy frameworks.

The foam manufacturing industry will benefit from detailed insights into potential end-of-life management options for their products, enabling them to adopt more sustainable production practices and potentially participate in extended producer responsibility schemes. Academic institutions will gain access to pioneering research in the Kenyan context, with the findings being disseminated through peer-reviewed journal publications, conference presentations, and integration into relevant course curricula. This will contribute to the growing body of knowledge on sustainable waste management practices in developing economies.

The research results will be disseminated through multiple channels to ensure widespread accessibility. These include submission to peer-reviewed academic journals focusing on waste management and renewable energy; presentation at relevant national and international conferences; preparation of policy briefs for government stakeholders; organization of stakeholder workshops involving industry representatives, policymakers, and academia; and deposit of the full dissertation in the university's digital repository for open access. Additionally, key findings will be shared with relevant professional associations and industry bodies in the polyurethane and waste management sectors through technical reports and presentations. This multi-channel dissemination strategy ensures all stakeholders can access and utilize the research findings according to their needs and interests.

1.8 Report Organization

This dissertation is structured to guide the reader logically through the study's context, methodology, results, and implications. Chapter 1 introduces the background and objectives, culminating in this report organization section to outline the subsequent chapters. Chapter 2 presents a comprehensive review of relevant literature on polyurethane flexible foam waste, energy recovery technologies, technical and economic analysis methods, and similar studies that have been done before in other jurisdictions that relate to the topic of study. Chapter 3 describes the methodology, including secondary data collection and analysis procedures, thermochemical modelling techniques, and the economic assessment framework. Chapter 4 details the results of waste generation estimates, calorific value determinations, and comparative performance analyses of fluidized beds versus mass burn incineration systems. Chapter 5 discusses these findings in the context of technical viability and cost-effectiveness, comparing them with published benchmarks and highlighting limitations.

Chapter 2: Literature Review

2.1 Introduction

This chapter has two parts: the theoretical and empirical literature review. The theoretical literature review is focused on providing a general overview of Polyurethane (P.U.), explaining the applications of Polyurethane Foams, and discussing the types and sources of P.U. Waste. Furthermore, it delves into the specifics of Post post-consumer polyurethane Foam Waste and Post-consumer Flexible Polyurethane Foam Waste. Additionally, it explores incineration as an Energy Recovery Technology and Techno-Economic Feasibility Assessment.

The empirical review section of the literature review is centred on reviewing similar studies and research done in the past, highlighting their relevance and linking to the study topic. These studies and research will identify possible gaps and limitations in analyzing energy recovery from Post-Consumer Polyurethane Flexible Foam Waste (PCPUFFW) through incineration. It identifies the need to address gaps in understanding the energy recovery potential from post-consumer flexible foam waste within the Kenyan market.

Moreover, the empirical review section aims to fill the gap in empirical research related to the feasibility assessment and energy implications of incinerating P.U. foam waste, explicitly focusing on the Kenyan context. Furthermore, it aims to provide insight into potential limitations during incineration and energy recovery from P.U. foam waste.

2.2 Theoretical Literature Review

2.2.1 Polyurethane Overview

Polyurethane foams constitute a versatile class of polymeric materials widely employed across various industries, given their unique features and diverse use. These foams are derived from the reaction between isocyanates and polyols facilitated by catalysts and additives (Randall & Lee, 2002). The fundamental chemical reaction involved in the formation of polyurethane is depicted as follows:

$$R\text{-}N{=}C{=}O + R'\text{-}OH \rightarrow R\text{-}NH\text{-}CO\text{-}O\text{-}R'$$

Isocyanate + Polyol = Urethane linkage

Equation 2.1

This reaction yields a thermosetting polymeric structure characterized by alternating urethane linkages and hydrocarbon segments, which impart specific properties to the resulting foam (Akindoyo et al., 2016).

Polyurethane foams are broadly categorized into two types depending on their chemical composition and physical properties: rigid and flexible. A closed-cell structure characterizes rigid polyurethane foams and exhibits high thermal insulation, compressive Strength, and dimensional stability (Zhu et al., 2021). Conversely, flexible polyurethane foams possess an open-cell structure, contributing to their softness, flexibility, and resilience (Szycher, 2012).

The physical features of polyurethane foams are primarily influenced by their chemical structure, the type and ratio of reactants, and the presence of additives. Table 1 compares the typical physical features of stiff and flexible polyurethane foams.

Table 2.1: Physical Properties of Rigid and Flexible Polyurethane Foams

Property	**Rigid Polyurethane Foam**	**Flexible Polyurethane Foam**
Density (kg/m^3)	30 – 300	15 - 80
Compressive Strength (kPa)	150 – 700	3 - 50
Tensile Strength (kPa)	200 – 900	50 - 500
Elongation at Break (%)	3 – 10	50 - 250
Thermal Conductivity (W/m·K)	0.018 - 0.035	0.030 - 0.050

Table 2.1 shows the Physical Properties of Rigid and Flexible Polyurethane Foams according to M. Szycher (2012). The cellular structure of polyurethane foams can be further classified based on the presence or absence of interconnected cells. Open-cell foams exhibit interconnected cells, allowing air and moisture to permeate through the foam. In contrast, closed-cell foams have isolated, non-interconnected cells, resulting in improved insulation properties and reduced permeability (Neelapala et al., 2019).

2.2.2 Applications of Polyurethane Foams.

The diverse array of properties exhibited by polyurethane foams has facilitated their widespread adoption across numerous industries. The construction sector represents a significant consumer of polyurethane foams, leveraging their insulation and structural properties in various uses, such as sandwich panels, insulation panels, and spray foam insulation (Szycher, 2012).

The furniture industry is another significant consumer of exceptionally flexible polyurethane foams due to their cushioning properties and comfort characteristics (Neelapala et al., 2019). Automotive applications, such as seating, headrests, and interior trim, also contribute to the demand for polyurethane foams, leveraging their lightweight and energy-absorbing properties (Zhu et al., 2021).

Table 2 presents the global polyurethane foam market volume by application in 2020 and the projected demand for 2028, highlighting the dominant role of the construction industry.

Table 2.2: Global Polyurethane Foam Market Volume by Application

Application	Market Volume (Million Tons) 2020
Construction	5.2
Furniture	2.8
Automotive	2.1
Packaging	1.6
Others	1.3
Total	13.0

Table 2.2 shows the Global Polyurethane Foam Market Volume by Application according to Grand View Research (2022). The Asia-Pacific region, pushed by fast urbanization and industrialization in areas like India and China, accounts for nearly half of the global polyurethane foam production capacity, followed by Europe and North America (Stratview Research, 2021). This regional distribution underscores the globalized nature of the polyurethane foam industry and the varying demand patterns across diverse economies.

2.2.3 Types and Sources of P.U. Waste

It is essential first to understand the different applications of P.U. products, which include but are not limited to rigid P.U. products for insulation, PU CASE materials (coatings, adhesives, sealants, and elastomers), and P.U. foam products (mattresses, cushions, pillows) with a particular focus on P.U. foam waste and its associated sources.

Rigid PU products are widely used for thermal insulation applications in buildings, refrigeration, and appliances. According to Ron and Kathy (1997), using rigid P.U. foam as insulation materials in buildings discusses their advantageous properties, such as low heat conductivity and high compressive Strength. P.U. Case Materials (Coatings, Adhesives, Sealants, and Elastomers) encompass many applications, including coatings, adhesives, sealants, and elastomers. According to Sonneschein and Mark F (2014), P.U. adhesives have a significant role in bonding different substrates in various industries, including automotive and construction.

P.U. Foam Products will be the focus of this study. P.U. foam products, such as mattresses, cushions, and pillows, are ubiquitous in the furniture and bedding industries. They provide comfort and support, contributing to their widespread use. Szycher (2012) elaborates on the production and application of P.U. foam products in the bedding industry, discussing their properties and applications. The popularity of P.U. foam products in the furniture and bedding industries results in significant waste generation, including chemical wastes during processing, cut-offs, trim-offs during block cutting and conversion, and end-of-life P.U. foam waste.

2.2.3.1 Post-Consumer Polyurethane Foam Waste

Post-consumer polyurethane foam waste represents a significant waste stream that necessitates effective management strategies to mitigate its environmental impact and harness its potential as a valuable resource. This waste stream originates from various sources, including discarded furniture, automotive components, construction and demolition activities, and end-of-life consumer products (Zia et al., 2007). Post-consumer polyurethane foam waste generation rates are closely tied to the respective industries' and regions' consumption patterns and disposal practices. Table 3 shows the estimated world generation rates of polyurethane foam waste in the sectors in 2020.

Table 2.3: Global Generation Rates of Polyurethane Foam Waste by Sector (2020)

Sector	Generation Rate (Million Tons)
Furniture and Bedding	3.8
Automotive	1.5
Construction and Demolition	2.1
Others	1.2
Total	8.6

Table 2.3 above shows the Global Generation Rates of Polyurethane Foam Waste by Sector in 2020, as reported by the International Solid Waste Association (2021). Post-consumer polyurethane foam waste management presents several challenges due to its complex chemical composition and physical properties. Polyurethane foams are typically composed of a crosslinked polymer network formed by the reaction between isocyanates and polyols, as represented by the following generalized chemical equation:

R and R' represent hydrocarbon segments, and n is the number of repeating units in the polymer chain (Akindoyo et al., 2016).

$$n\ OCN\text{-}R\text{-}NCO + n\ HO\text{-}R'\text{-}OH \rightarrow [\text{-}NHCOO\text{-}R\text{-}OOCNH\text{-}R'\text{-}]\ n + CO2$$

Isocyanate + Polyol = Polyurethane

Equation 2.2

The cross-linked structure of polyurethane foams renders them resistant to biodegradation and thermal degradation, posing challenges for recycling and disposal (Noreen et al., 2020). Additionally, various additives, such as flame retardants, catalysts, and blowing agents, can further complicate waste management.

Improper disposal of post-consumer polyurethane foam waste can have detrimental environmental consequences. Landfilling can lead to the generation of landfill gases, such as methane, and the leaching of harmful substances into groundwater (Zia et al., 2007). Incineration, while offering a potential energy recovery route, may result in the emission of toxic pollutants, including dioxins and furans, if not adequately controlled (Ionescu et al., 2020).

Various waste management strategies have been explored to address these challenges, including mechanical recycling, chemical recycling, and energy recovery through incineration and pyrolysis (Noreen et al., 2020). However, the feasibility and viability of these approaches are influenced by factors such as the availability of appropriate technologies, economic considerations, and regulatory frameworks.

2.3.3.2 Post-Consumer Flexible Polyurethane Foam Waste

Within the broader category of post-consumer polyurethane foam waste, a significant portion originates from the disposal of flexible polyurethane foams used in comfort uses such as seating, bedding, and cushions. These foams, defined by their open-cell structure and high resilience, are widely employed in the furniture and automotive industries to provide cushioning and support (Szycher, 2012).

The current waste management infrastructure for post-consumer flexible polyurethane foams varies across regions and jurisdictions. In many developed countries, these foams are typically collected through municipal solid waste streams or dedicated recycling programs, although the latter remains limited in scope (Ionescu et al., 2020). Developing nations often lack comprehensive collection and disposal systems, leading to improper disposal methods, such as open burning or landfilling, which can have severe environmental consequences (Noreen et al., 2020).

The management of post-consumer flexible polyurethane foam waste poses several challenges. Firstly, various additives, such as flame retardants and dyes, can complicate recycling processes and limit the potential for material recovery (Amaral et al., 2018). Secondly, these foams' open-cell structure and high resilience make them resistant to conventional mechanical recycling processes, such as shredding and densification (Noreen et al., 2020). Furthermore, the heterogeneity of the waste stream, which may contain a mixture of different types of polyurethane foams and contamination from other materials, adds complexity to the sorting and separation processes required for effective recycling (Ionescu et al., 2020).

To tackle these issues, various approaches have been proposed and explored. Chemical recycling techniques, such as glycolysis and hydrolysis, offer potential routes for breaking down the polyurethane structure and recovering valuable components like polyols and di-isocyanates (Amaral et al., 2018). However, these processes often require specialized equipment and can be energy-intensive, impacting economic viability.

Energy recovery through incineration or pyrolysis has also been proposed as an alternative approach, leveraging polyurethane foams' high calorific value and combustible nature (Ionescu et al., 2020). These processes direct waste from landfills and generate energy through heat or syngas, which can be utilized for various applications, including electricity generation. Nonetheless, the implementation of energy recovery systems requires careful consideration of emission control measures to mitigate the potential production of harmful pollutants, such as nitrogen oxides (NO_x), carbon monoxide (CO), and dioxins (Noreen et al., 2020). Additionally, the economic viability of such systems has contributing factors such as the scale of operations, feedstock availability, and energy market dynamics.

A comprehensive approach involving legislative measures, technological advancements, and stakeholder collaboration is necessary to facilitate the effective management of post-consumer flexible polyurethane foam waste. This may include the implementation of extended producer responsibility (EPR) schemes, the development of advanced recycling technologies, and the establishment dedicated collection and sorting infrastructure (Amaral et al., 2018; Ionescu et al., 2020).

2.3.4 Incineration as an Energy Recovery Technology:

Incineration is a well-established thermal treatment process that plays a vital role in waste-to-energy (WtE) systems. The underlying principle of incineration includes the controlled burning of waste materials at high temperatures between 850°C and 1100°C (Leckner, 2015). This process converts the chemical energy stored in the waste into heat energy, which can be retrieved and used for various applications, including steam generation for electricity production or district heating.

The following generalized equation can represent the overall combustion reaction in an incineration process:

$$\textit{Waste (C, H, O, N, S) + Air (O2, N2)} \rightarrow \textit{CO2 + H2O + N2 + SO2 + Heat}$$

Equation 2.3

Where***:***

C	Carbon dioxide (CO_2)
H	Water vapour (H_2O)
O	Oxygen (O_2)
N	Nitrogen (N_2)
S	Sulfur dioxide (SO_2)

Several incineration technologies have been developed and implemented, each with unique characteristics and suitability for different waste streams and applications.

2.3.4.1 Mass Burn Incineration:

Mass burn incineration is one of the most commonly employed and advanced technologies for municipal solid waste (MSW) and industrial waste treatment. The waste is fed directly into a combustion chamber without prior sorting or processing (Themelis & Mussche, 2014). The combustion chamber, also known as the furnace, typically includes a grate system where the waste is burned, and the heat generated is recovered through boilers or heat exchangers.

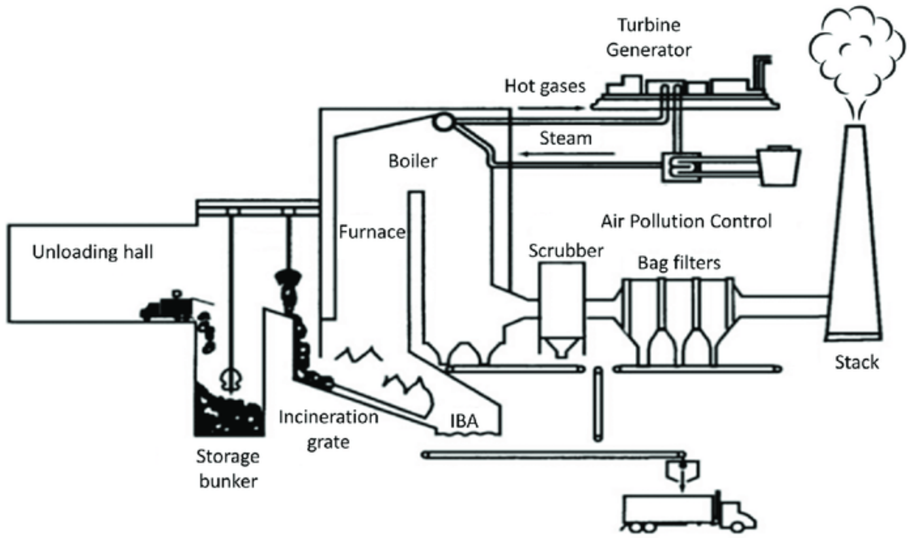

Figure 2.1: **Schematic representation of a mass burn incineration system. Smith, J. (2020)**

The mass burn process is suitable for handling large volumes of mixed waste streams, eliminating the need for extensive pre-sorting. However, additional air pollution control systems may be required to mitigate the emissions of pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) (Themelis & Mussche, 2014).

2.3.4.2 Fluidized Bed Incineration:

Fluidized bed incineration technology applies a bed of inert particles, which includes sand or ash, fluidized by introducing air from the bottom (Leckner, 2015). The waste is fed into this fluidized bed, which undergoes rapid and efficient combustion due to the bed particles' high surface area and uniform air distribution.

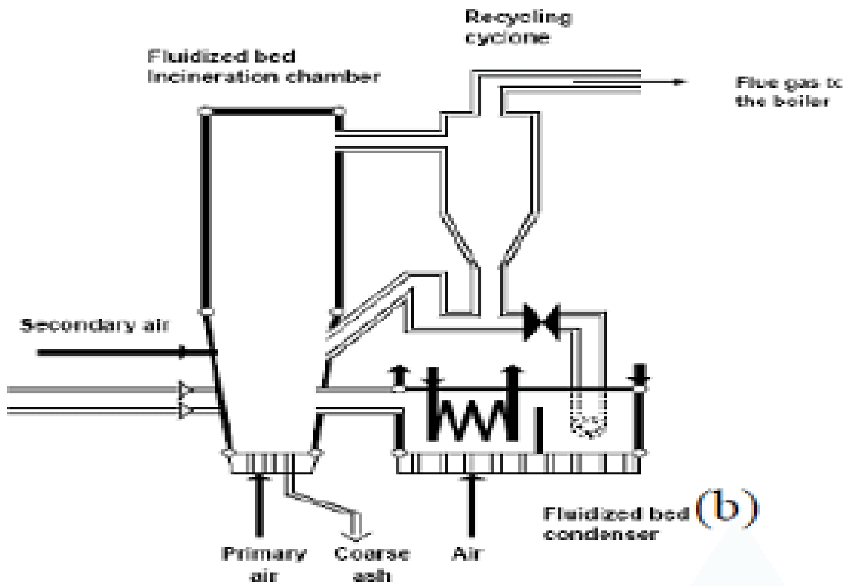

Figure 2.2: Schematic representation of a fluidized bed incineration system. Basu, P. (2015).

Fluidized bed incinerators offer several advantages, including good mixing and heat transfer, high combustion efficiency, and handling of various waste types and particle sizes (Leckner, 2015). The fluidized bed can also sink sulfur dioxide (SO2) emissions when limestone or dolomite is added to the bed, reducing the need for additional flue gas treatment (Koornneef et al., 2007).

The temperature distribution within a fluidized bed can be approximated by the following equation (Kunii & Levenspiel, 1991)

$$T_z = T_0 + (T_{max} - T_0)\left(1 - exp\,\frac{kz}{u}\right)$$

Equation 2.4

Where;

T_z	Temperature at height z
T_0	Inlet temperature
T_{max}	Maximum temperature
K	Rate constant
Z	Height above the distributor plate
U	The superficial gas velocity

2.3.4.3 Rotary Kiln Incineration:

Rotary kiln incinerators are designed to handle a wide range of waste types, including industrial hazardous waste, medical waste, and certain types of municipal solid waste (Leckner, 2015). These systems consist of a slightly inclined refractory-lined rotating cylindrical vessel that allows the waste to move through the Kiln as it rotates.

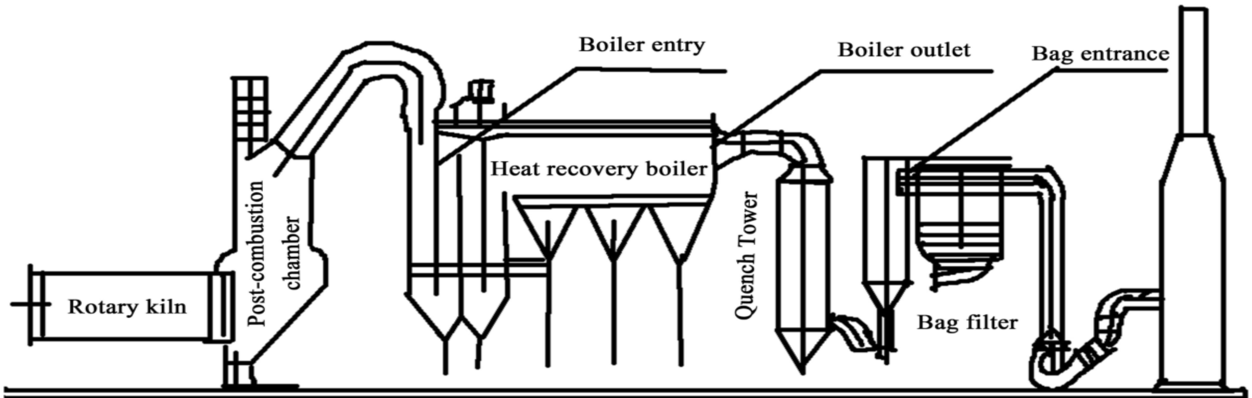

Figure 2.3: Schematic representation of a rotary kiln incineration system. Theodore, L., & Reynolds, J. P. (2007)

The waste is fed into the elevated end of the Kiln, where it undergoes drying, pyrolysis, and combustion as it moves through it (Leckner, 2015). Rotary kilns offer high thermal efficiency and can handle diverse waste streams, including those with high moisture content or calorific value.

The residence time of the waste in the rotary Kiln is determined by the equation below (Niessen, 2010):

$$t = \frac{L}{60N\, tan(\alpha)}$$

Equation 2.5

Where;

T	The residence time in minutes
L	Length of the Kiln in meters
N	Rotational speed
A	Inclination angle in degrees

Table 2.4: Critical Characteristics of Incineration (Leckner (2015), Themelis & Mussche (2014).

Technology	Waste Types	Temperature Range	Advantages	Disadvantages
Mass Burn	Municipal Solid Waste	850°C - 1100°C	Simple design handles mixed waste	High emissions require flue gas treatment
Fluidized Bed	Municipal/Industrial Waste	850°C - 950°C	Good mixing, high efficiency	Complex design, bed material required
Rotary Kiln	Hazardous/Industrial Waste	900°C - 1200°C	Handles diverse waste streams	High capital and operating costs

The type of incineration technology is based on various attributes such as the waste composition, desired energy recovery, emission control requirements, and economic considerations.

2.3.5 Techno-Economic Feasibility Assessments:

Techno-economic feasibility assessments are crucial to evaluate the viability and profitability of a proposed project, technology, or process from both technical and economic considerations. These assessments comprehensively analyze the technical feasibility, economic viability, and potential risks associated with implementing and operating a particular system or technology (Towler & Sinnott, 2013).

In the context of waste-to-energy (WtE) technologies, techno-economic feasibility assessments significantly influence the proposed solutions' economic attractiveness and long-term sustainability. These assessments typically involve the following vital parameters and methodologies:

1. Technical Analysis:
    i. Process modelling and simulations
    ii. Mass and energy balances
    iii. Equipment sizing and selection
    iv. Environmental impact assessment
    v. Operational requirements and constraints
2. Economic Analysis:
    i. Capital cost estimation (equipment, installation, land)
    ii. Operating cost estimation (labor, utilities, maintenance)

iii. Revenue projections (energy sales, tipping fees, by-product sales)
iv. Financial metrics
v. Sensitivity and risk analyses

2.3.5.1 Technical Analysis

The technical analysis typically involves the following steps:

a. Process Modelling and Simulations

Process modeling and simulations depend on mass and energy balances, thermodynamic principles, and kinetic models of the involved processes. The following equation can represent the overall mass balance for a WtE process:

$$\Sigma\, Input\ streams = \Sigma output\ streams + Accumulations$$

Equation 2.6

Where energy inputs include the chemical energy of the feedstock and external energy sources such as fuel & electricity, and energy outputs represent the desired energy product derivatives such as heat, electricity, and waste heat streams.

b. Equipment Sizing and Selection:

The appropriate equipment can be sized and selected based on the process simulations and mass/energy balances. This includes reactors, heat exchangers, pumps, compressors, and emission control systems. Equipment sizing often involves empirical correlations, design equations, and industry standards. For example, the sizing of a fluidized bed reactor for waste incineration can be based on the following equation (Kunii & Levenspiel, 1991):

$$Ar = (\rho p - \rho g) * g * Dp^3 * \frac{\rho g}{\mu^2 * (1 - \varepsilon mf)}$$

Equation 2.7

Where;

Ar	Archimedes number
Pp	Density of particle
Pg	Density of gas
Dp	Particle diameter
M	Gas viscosity
Emf	Minimum fluidization voidage

c. Environmental Impact Assessment:

An essential aspect of the technical analysis is assessing the potential ecological outcomes of the proposed WtE system. This includes evaluating emissions, waste streams, and their potential effects on air, water, and soil quality. Environmental impact assessment models and simulations are employed to quantify and mitigate these impacts. For instance, the dispersion of air pollutants from a WtE facility can be modelled using atmospheric dispersion models, such as the Gaussian plume model:

$$C(x,y,z) = \frac{Q}{2\pi * \ \sigma y \ * \ \sigma z \ * \ u} * exp\left(-\frac{Y^2}{2 * \sigma z^2}\right) * exp\left(-\frac{(z-H)^2}{2 * \sigma z^2}\right) + exp\left(-\frac{(z+H)^2}{2 * \sigma z^2}\right)$$

Equation 2.8

Where;

C(x, y, z)	Pollutant concentration
Q	Emission rate
Σy	Horizontal dispersion coefficient
Σz	Vertical dispersion
U	Wind speed
H	Effective stack height

d. Operational Requirements and Constraints:

The technical analysis also considers the operational requirements and constraints of the WtE system, such as feedstock characteristics, energy demand profiles, maintenance schedules, and regulatory compliance. These factors are crucial in ensuring the system's efficient and reliable operation.

2.3.5.2 Economic Analysis:

The economic analysis typically involves the following steps:

2.3.5.2.1 **Capital Cost Estimation:**

Capital costs represent the initial investment required to implement the WtE project. These costs include equipment purchase, installation, land acquisition, site preparation, and construction. Capital cost estimation can be performed using various methods, such as factorial, bottom-up Estimation, and cost correlations. The TCI is determined using the following equation (Towler & Sinnott, 2013):

$$TCI = FCI + OSBL + Working\ Capital$$

Equation 2.9

Where***;***

FCI	Fixed capital investment (equipment, installation, instrumentation)
OSBL	Outside battery limits (costs related to utilities, infrastructure, and site preparation)
Working capital	Initial funds needed for the operation

2.3.5.2.2 Operating Cost Estimation:

Operating costs represent the recurring expenses associated with the operation and maintenance of the WtE system. These costs include labour, utilities (e.g., electricity, water, fuel), consumables, waste disposal, and maintenance. The total operating cost (TOC) can be estimated using the following equation:

$$TOC = Fixed\ Operating\ Costs + Variable\ Operating\ Costs$$

Equation 2.10

Fixed Operating Costs include expenses like labour, overhead, and maintenance, while Variable Operating Costs are directly proportional to the system's throughput or production rate, such as utilities and consumables.

2.3.5.2.3 Revenue Projections:

Revenue projections account for the potential income streams generated by the WtE system. These may include revenues from energy sales (electricity, heat), tipping fees for waste processing, and by-products or recovered materials sales. The annual revenue (A.R.) can be calculated as:

$$AR = (Energy\ Sales) + (Tipping\ Fees) + (By - product\ Sales)$$

Equation 2.11

Energy sales represent the revenue from selling electricity, heat, or other energy products; Tipping Fees are the fees charged for processing the waste, and by-product sales include revenue from selling recovered materials or by-products.

2.3.5.2.4 Financial Metrics:

Financial metrics are used to assess the economic viability and profitability of the WtE project. These metrics are:

Net Present Value (NPV): this represents the sum of the present values of the annual cash flows over the project lifetime, discounted at a specified rate.

$$NPV = \Sigma\ (Annual\ Cash\ Flow\ /\ (1 + r)\hat{}t)$$

Equation 2.12

Where:

r is the discount rate, and t is the period.

Internal Rate of Return (IRR): This discount rate makes the NPV equal to zero.

$$NPV = 0 = \Sigma\ (Annual\ Cash\ Flow\ /\ (1 + IRR)\hat{}t)$$

Equation 2.13

The payback Period is the time required to recover the initial capital investment from the project's cash flows.

2.3.5.2.5 Sensitivity and Risk Analyses:

Sensitivity and risk analyses are performed to evaluate the impact of uncertainties and variabilities in the input parameters on the project's economic performance. These analyses help identify critical factors and potential risks, allowing for informed decision-making and mitigation strategies.

2.3.5.3 Feasibility Analysis – Methods and Tools

Several methodologies and tools are employed in techno-economic feasibility assessments, including process simulation software, cost estimation techniques (e.g., factorial methods, bottom-up Estimation), and financial modelling tools. These methodologies facilitate the integration of technical and economic data, enabling comprehensive analyses and informed decision-making.

The importance of economic viability in adopting WtE technologies cannot be overstated. Despite the potential environmental and energy recovery benefits offered by WtE solutions, their implementation and long-term sustainability are heavily influenced by economic considerations.

Factors such as feedstock availability, energy prices, operational costs, and market conditions can influence the competitiveness and profitability of WtE projects (Tan et al., 2015).

By integrating technical and economic analyses, techno-economic feasibility assessments facilitate the identification of cost-effective and sustainable solutions, fostering the adoption and successful implementation of WtE technologies in various jurisdictions and industries (Tan et al., 2015; Towler & Sinnott, 2013).

2.4 Empirical Review

The University of Sydney (2021) examined the feasibility of various waste-to-energy technologies, including incineration polyurethane foams and other plastics, for municipal solid waste management in Sydney, Australia. The key findings of the University of Sydney study were that incineration-based waste-to-energy projects showed promising economic feasibility for municipal solid waste management in Sydney. The research estimated that an incineration plant with a capacity of 500,000 tonnes per year could generate approximately 400 GWh of electricity annually, with an NPV of AUD 200 million and an IRR of 12% over a 25-year project life (University of Sydney, 2021).

However, there were some limitations associated with the study. Firstly, the study focused on the broader municipal solid waste stream and did not specifically analyze the techno-economic feasibility of using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. Secondly, the study was conducted in Sydney, Australia, with a specific waste management infrastructure, regulatory framework, and economic conditions. The findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Peng et al. (2022) conducted a comprehensive review of thermochemical technologies for energy recovery from municipal solid waste (MSW), emphasizing incineration, gasification, and pyrolysis. The review provided a detailed overview of each thermochemical conversion technology's principles, reactions, and products. For instance, the authors discussed the main reactions involved in the incineration process, such as the combustion of organic matter in excess air.

The study also presented a comparative analysis of different thermochemical conversion technologies' energy recovery potential and environmental performance. The authors found that incineration is the most mature and widely adopted technology for MSW treatment, with energy recovery efficiencies ranging from 20% to 30% for electricity generation and up to 80% for combined heat and power (CHP) systems (Peng et al., 2022).

While the comprehensive review by Peng et al. (2022) provided valuable insights into the thermochemical conversion technologies for MSW, it had some limitations concerning the proposed research topic. Firstly, the review focused on the broader MSW stream and did not specifically analyze the techno-economic feasibility of using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. Secondly, the review had a global perspective. It did not provide specific insights into the Kenyan or East African context, which may have unique waste management challenges, infrastructures, and socio-economic factors.

Ionescu et al. (2021) conducted a techno-economic analysis of energy recovery from waste polyurethane foams in the United Kingdom, focusing on incineration and pyrolysis processes. The process modeling stage involved the development of detailed models for incineration and pyrolysis processes using Aspen Plus software. The models simulated the mass and energy balances and the product yields and compositions based on the input waste polyurethane foam characteristics.

The study found that incineration and pyrolysis processes showed promising energy recovery potential for waste polyurethane foams. The incineration process had a higher energy recovery efficiency, with a net electrical efficiency of 25% and a thermal efficiency of 60%. The pyrolysis process had a lower energy recovery efficiency but produced valuable products such as pyrolysis oil and syngas (Ionescu et al., 2021).

The Study by Ionescu et al. (2021) had some limitations. Firstly, the study focused on the broader category of waste polyurethane foams and did not specifically analyze the techno-economic feasibility of using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. The research was based in the United Kingdom, which has a specific waste management infrastructure, regulatory framework, and economic conditions. The findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Mbande et al. (2020) comprehensively evaluated the waste-to-energy (WtE) potential in South Africa. The waste characterization stage involved the analysis of waste samples from different sources to determine their physical and chemical properties, such as moisture content, calorific value, and elemental composition. The authors used standard laboratory techniques, such as bomb calorimetry and ultimate analysis, to characterize the waste samples.

The study found that South Africa has a significant WtE potential, with an estimated 54 million tonnes of waste generated annually, of which 13 million tonnes are suitable for energy recovery. The authors estimated that the technical energy potential from these waste streams is approximately 200 PJ per year, which could contribute to 4% of South Africa's total energy supply (Mbande et al., 2020).

While the study by Mbande et al. (2020) provided valuable insights into the potential of WtE in South Africa, it had some limitations concerning the proposed research topic. Firstly, the study focused on the broader waste streams and did not specifically analyze the techno-economic feasibility of using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. Secondly, the study was conducted in the context of South Africa, which has a specific waste management infrastructure, regulatory framework, and economic conditions. Although South Africa is African, the findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Neelapala et al. (2019) conducted a study to quantify and characterize polyurethane foam waste in Australia and assess the opportunities for energy recovery through incineration and thermochemical processes. The scope of the study included the Estimation of post-consumer polyurethane foam waste generation, characterization of waste properties, and assessment of energy recovery potentials.

The waste characterization stage involved collecting and analyzing polyurethane foam waste samples from different sources, such as furniture, automotive, and construction sectors. The authors used standard laboratory techniques, such as thermogravimetric analysis (TGA) and bomb calorimetry, to determine the thermal and chemical properties of the waste samples.

The study found that Australia generates approximately 150,000 tonnes of polyurethane foam waste annually, with the furniture and bedding sector being the most significant contributor. The authors estimated that the theoretical energy potential of this waste is around 4.5 PJ per year. In comparison, the technical energy potential ranges from 1.8 to 3.6 PJ per year, depending on the energy recovery technology (Neelapala et al., 2019).

While the Study by Neelapala et al. (2019) provided valuable insights into the quantification and characterization of polyurethane foam waste in Australia, it had some limitations concerning the proposed research topic. Firstly, although the study focused on post-consumer polyurethane foam waste, it did not specifically analyze the techno-economic feasibility of using flexible polyurethane foam waste from comfort applications as the sole feedstock for incineration. Secondly, the study was conducted in the context of Australia, which has a specific waste management infrastructure, regulatory framework, and economic conditions. The findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Saeed et al. (2017) employed a multi-criteria decision analysis (MCDA) approach, which involved the integration of technical, economic, and environmental criteria into a single assessment framework. They used the Analytic Hierarchy Process (AHP) to determine each criterion's relative importance and rank the WtE technologies based on their overall performance.

The study found that WtE technologies have significant potential in Canada for energy recovery and GHG emission reduction. The authors estimated that the total energy recovery potential from MSW and industrial waste in Canada is approximately 250 PJ per year, equivalent to 69 TWh of electricity and 181 PJ of Heat (Saeed et al., 2017. The MCDA results indicated that incineration is Canada's most preferred WtE technology, followed by gasification and anaerobic digestion, considering the combined technical, economic, and environmental criteria.

While the Study by Saeed et al. (2017) provided valuable insights into the WtE opportunities in Canada, it had some limitations concerning the proposed research topic. Firstly, the study focused on a broad range of waste streams and did not specifically analyze the techno-economic and environmental feasibility of using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. Secondly, the study was conducted in the context of Canada, which has a specific waste management infrastructure, regulatory framework, and economic conditions. The findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Nakamura et al. (2016) conducted a study to estimate the levelized cost of electricity (LCOE) for waste-to-energy (WtE) plants in Japan, considering various feedstocks, including municipal solid waste (MSW) and industrial waste, such as polyurethane foams. The scope of the study included the evaluation of the economic viability of WtE plants and identifying key factors influencing the LCOE. The researchers employed a cost-based approach to calculate the LCOE for WtE plants.

The authors collected data on the capital costs, operation and maintenance costs, waste disposal costs, and electricity generation of existing and planned WtE plants in Japan. They also considered different scenarios for the key parameters, such as the plant capacity, waste composition, and energy efficiency, to assess their impact on the LCOE.

The study found that the LCOE for WtE plants in Japan ranges from 10 to 25 yen/kWh (approximately 0.09 to 0.23 USD/kWh), depending on the plant capacity, waste composition, and energy efficiency (Nakamura et al., 2016). The authors identified that the plant capacity and waste disposal cost are the most significant factors affecting the LCOE. The authors found that a 10% increase in the waste disposal cost could lead to a 5-7% increase in the LCOE, while a 10% improvement in energy efficiency could result in a 3-5% decrease in the LCOE.

While the Study by Nakamura et al. (2016) provided valuable insights into the LCOE for WtE plants in Japan, it had some limitations concerning the proposed research topic. Firstly, although the study considered various feedstocks, including polyurethane foams, it did not specifically focus on the LCOE for WtE plants using post-consumer flexible polyurethane foam waste from comfort applications as the sole feedstock. Secondly, the study was conducted in the context of Japan, which has a specific waste management infrastructure, regulatory framework, and economic conditions. The findings and recommendations may not directly apply to the Kenyan or East African regions, which may have different waste management challenges, infrastructures, and socio-economic factors.

Other additional studies, such as the study by the European Commission's Joint Research Centre (JRC) (2019), aim to provide an in-depth assessment of the existing state of polyurethane foam recycling in the European Union (E.U.). The scope of the study encompassed various recycling methods, including mechanical, chemical, and energy recovery, with a particular emphasis on the technical and economic attributes of these processes. The key finding was the identification of energy recovery through incineration as a viable option for polyurethane foam waste management. The report highlighted the potential for energy recovery from the high calorific value of polyurethane foams, which can range from 20 to 30 M.J./kg (JRC, 2019).

Similarly, the research by the Japanese Ministry of Economy, Trade, and Industry (METI) (2017) confirmed the high energy content of polyurethane foam waste. Experimental results showed that the average higher heating value (HHV) of polyurethane foam waste samples ranged from 25 to 30 M.J./kg (METI, 2017), comparable to other standard fuels, such as coal and natural gas.

2.5 Empirical Review - Summary Table

Authors (Year)	Study Title / Focus	Key Findings	Gaps
University of Sydney (2021)	Feasibility of various WtE technologies (including PU foam incineration) for municipal solid waste in Sydney, Australia	A 500,000 t/yr incineration plant could generate ~400 GWh of electricity annually, with an NPV of AUD 200 M and IRR of 12 % over 25 years.	Broader MSW stream—did not isolate post-consumer flexible PU foam as sole feedstock.
Peng et al. (2022)	Comprehensive review of thermochemical conversion technologies (incineration, gasification, pyrolysis) for MSW energy recovery	Incineration is most mature: electrical efficiencies of 20–30 % and up to 80 % for CHP systems.	Global MSW focus—no PU-foam-specific analysis.
Ionescu et al. (2021)	Techno-economic analysis of incineration vs pyrolysis of waste PU foams in the UK, using Aspen Plus process modelling	Incineration yielded 25 % net electrical and 60 % thermal efficiency; pyrolysis produced valuable oil and syngas but lower overall energy recovery.	Considered mixed PU foam waste, not exclusively flexible PU;
Mbande et al. (2020)	Assessment of WtE potential from municipal and industrial wastes in South Africa	South Africa generates ~54 Mt/yr of waste, of which 13 Mt are suitable for energy recovery—potential ~200 PJ/yr (~4 % of national energy supply).	Broad waste categories—no focus on PU foam;
Neelapala et al. (2019)	Quantification and characterization of PU foam waste in Australia and its energy recovery potential via incineration and thermochemical processes	Australia generates ~150,000 t/yr PU foam waste; theoretical energy ~4.5 PJ/yr, with technical recovery of 1.8–3.6 PJ/yr depending on technology.	Did not perform techno-economic feasibility specifically for flexible PU foam;

2.6 Conceptual Framework

The conceptual framework illustrates the systematic approach to evaluating the techno-economic feasibility of energy recovery from post-consumer polyurethane flexible foam waste through incineration in Kenya. The framework encompasses four primary components: input factors, process analysis, economic factors, and external factors, all converging to generate the study's key outputs.

The input factors form the foundation of the analysis, comprising raw material import data (TDI and Polyol), production statistics (foam types, densities, and volumes), population and economic indicators, and product lifecycle information, including durability tests and disposal patterns. These inputs feed into the process analysis phase, where three crucial analytical steps are performed: waste generation assessment, energy content analysis, and energy conversion analysis. The waste generation assessment involves volume estimation and geographic distribution analysis, while the energy content analysis examines calorific values and material properties. The energy conversion analysis evaluates thermal and electrical efficiencies along with system losses.

Parallel to the process analysis, economic factors are considered, including capital costs (land, equipment, and engineering), operating costs (labour, maintenance, and utilities), and market factors (electricity prices and feed-in tariffs). The framework acknowledges the influence of external factors, such as the regulatory environment, environmental standards, technology availability, and infrastructure capacity, which impact both the process and economic analyses.

These interrelated components culminate in three primary outputs: waste generation rates and projections, energy recovery potential, and the Levelized Cost of Electricity (LCOE) with associated economic viability assessments. The framework demonstrates the complex interplay between technical, economic, and environmental factors in determining the feasibility of waste-to-energy conversion through incineration, providing a structured approach to addressing the research objectives.

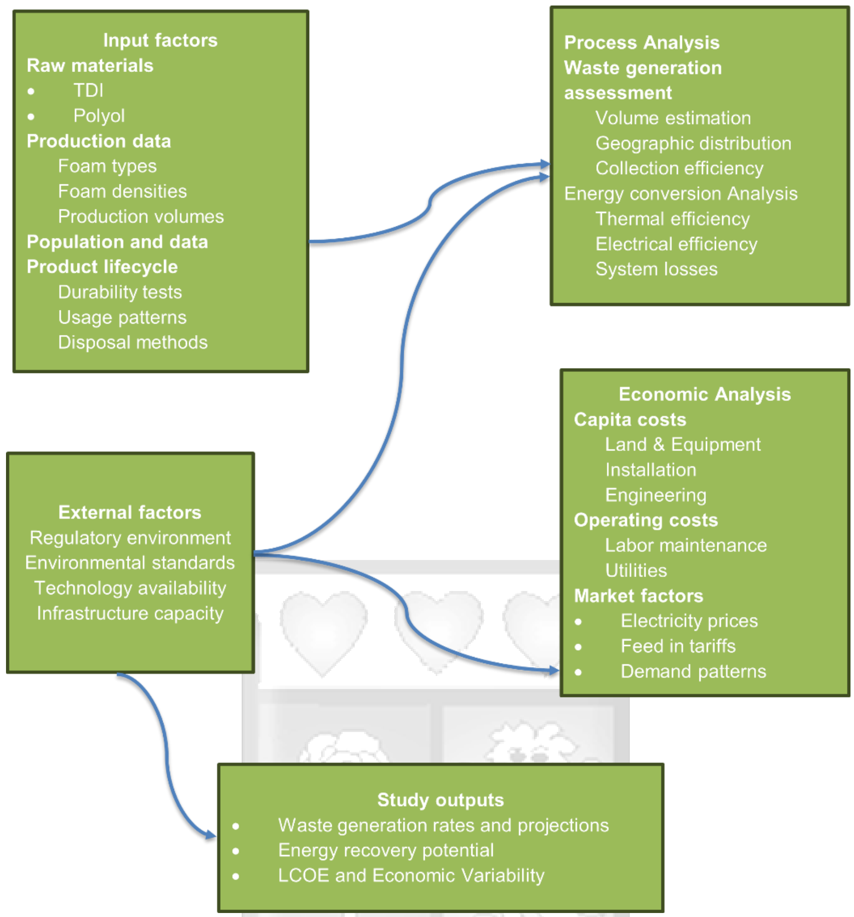

Figure 2.4: Conceptual framework

2.7 Research Gaps.

After reviewing the above studies on waste-to-energy (WtE) technologies, with a focus on polyurethane foam waste, several gaps and limitations have been identified. These gaps and limitations are summarized below, grouped by common themes, and presented sequentially.

Limited focus on post-consumer flexible polyurethane foam waste: Many of the reviewed studies, such as those by Peng et al. (2022), Mbande et al. (2020), and Saeed et al. (2017), focused on a broad range of waste streams, including municipal solid waste (MSW) and various industrial wastes. While some studies, like Ionescu et al. (2021) and Neelapala et al. (2019), specifically addressed polyurethane foam waste, they did not exclusively focus on post-consumer flexible polyurethane foam waste from comfort applications, which is the primary interest of the proposed research.

Lack of techno-economic feasibility assessments specific to Incineration: Several studies, such as Srirachat et al. (2019) and the National Renewable Energy Laboratory (2020), investigated the techno-economic feasibility of converting waste plastics, including polyurethane foams, into biofuels through pyrolysis or other thermochemical processes. However, there is a lack of comprehensive techno-economic feasibility assessments specifically targeting the incineration of post-consumer flexible polyurethane foam waste for energy recovery.

Limited applicability to the Kenyan or East African context: Most of the reviewed studies were conducted in the context of developed countries or regions, such as the European Union (JRC, 2019), the United States (NREL, 2020), Japan (METI, 2017; Nakamura et al., 2016), Australia (University of Sydney, 2021; Neelapala et al., 2019), and Canada (Saeed et al., 2017). While some studies focused on developing countries, such as Thailand (Srirachat et al., 2019) and South Africa (Mbande et al., 2020), there is a lack of research specifically tailored to the Kenyan or East African context, which may have unique waste management challenges, infrastructures, and socio-economic factors.

To address these gaps and limitations, the proposed research aims to conduct a targeted techno-economic feasibility assessment for energy recovery via the incineration of post-consumer flexible polyurethane foam waste in Kenya. By focusing on the specific feedstock, tailoring the study to the local context, and integrating environmental impact considerations, the research seeks to provide more relevant and actionable insights for effectively implementing regional waste-to-energy solutions.

2.8 Chapter Conclusion

This literature review has demonstrated that waste-to-energy (WtE) technologies—particularly incineration—are among the most mature and widely implemented solutions for managing municipal and industrial waste streams. Key studies reveal that incineration systems can achieve 20–30% electrical efficiencies and up to 80% thermal efficiencies in combined heat and power configurations, offering significant energy recovery potential from mixed solid wastes. However, most existing work focuses on broad waste categories or geographical contexts, such as Europe, Australia, and South Africa, without isolating post-consumer flexible polyurethane (PU) foam as a discrete feedstock. Moreover, techno-economic analyses often rely on secondary data or modelling assumptions that may not reflect the operational realities and cost structures present in East African waste management infrastructures.

The critical gap identified across these studies is the absence of context-specific data for Kenya's PU foam waste stream, including empirical measurements of calorific value, waste generation rates, and pilot-scale performance of incineration technologies. To address these shortcomings, the present study will quantify Kenya's annual post-consumer flexible PU foam waste generation, determine its net calorific value through laboratory assays, and perform a comparative techno-economic assessment of fluidized bed versus mass burn incineration systems under Kenyan cost and regulatory conditions. This research aims to inform policy, guide investment decisions, and advance sustainable WtE solutions tailored to Kenya's unique waste management challenges by providing empirical evidence and localized economic metrics.

Chapter 3: Research Methodology

3.1 Introduction

The methodology incorporates quantitative methods, experimental analysis, theoretical calculations, and economic assessment techniques to explain this waste-to-energy option's feasibility in the Kenyan context.

3.2 Research Design

The research used a quantitative research design, including collecting and analysing diverse secondary data sources (Kothari, 2004). This approach is suitable for the techno-economic feasibility assessment, as it integrates data from multiple sources to address the research objectives.

3.3 Estimation of Post-Consumer Flexible PU Foam Waste Generation

Estimating the rate of post-consumer flexible P.U. foam waste generation in Kenya involved modelling its relationship with key influencing factors such as population growth, economic development, furniture and mattress industry growth, product lifespan, and waste management practices (Hoornweg & Bhada-Tata, 2012).

3.3.1 Waste Generation Modeling

The waste generation model was developed based on the equation proposed by Hoornweg & Bhada-Tata (2012). The total municipal solid waste generation is calculated by multiplying the per capita waste generation by the total population and scaling it annually.

$$Wt = P \times V \times 365/1000$$

Equation 3.1

Where:

Wt is the total MSW in tones

P is the population

V is the Per Capita MSW in (kg/day)

Building up on equation 3.1, to get the total flexible PUF waste, the specific fraction of PU foam waste was estimated within the total waste generated by incorporating population, waste volume, and material-specific fractions (Malinauskaite et al., 2017; Ionescu et al., 2021).

$$FW = (P \times v) \times 365 \times P^f \times PU^f \times F^f)/1000$$

Equation 3.2

Where;

FW is Flexible PUF Waste (tons/year)

V is the Per Capita MSW in (kg/day)

P is the Population

P^f is the fraction of plastics in MSW (%)

PU^f is the fraction of polyurethane in plastic waste (%)

F^f is the fraction of flexible PUF in PU waste (%)

The waste generation model estimates per capita municipal solid waste (MSW) (V) based on urbanization rates, accounting for differences in waste production between urban and rural populations(Hoornweg & Bhada-Tata, 2012; Kaza, Yao, Bhada-Tata, & Van Woerden, 2018):.

$$V = (Ur \times Upc) + ((1 - Ur) \times Rpc)$$

Equation 3.3

Where:

V is the Per Capita MSW in (kg/day)

Ur is the Urbanization rate

Upc is the Per Capita Waste MSW (Urban)

Rpc: Per capita Waste MSW (Rural)

3.3.2 Calorific Value Analysis

This research used the approach as proposed by Mondal & Rafizul (2025), where to get refined calorific value, he incorporated proximate waste composition analysis to ensure a more accurate estimation of the effective energy potential of municipal solid waste. The research considered gross calorific value (GCV) to derive the net calorific value (NCV) by accounting for moisture and foreign matter content.

The governing equation for the NCV is given as,

$$NCV = GCV_{dry} \times P - (2.44 \times M)$$

Equation 3.4

Where:

GCV dry is the gross calorific value of dry PU foam waste in MJ/kg.

P is the fraction of dry PU foam in the waste

M represents the moisture fraction (%)

2.44 MJ/kg is the latent heat of vaporization of water

The fraction of dry PU foam (P) in the waste is determined by accounting for the presence of moisture(M) and foreign matter (F), which consists of non-PU materials such as contaminants or inert substances. The following equation governs this:

$$P = 1 - F - M$$

Equation 3.5

Where:

P is the fraction of dry PU foam in the waste

F is the foreign matter

M represents the moisture fraction (%)

3.3.3 Thermal & Electrical Evaluation

This research considered the thermal and electrical evaluation of flexible PUF waste to assess its potential as an energy source through incineration. Thermal evaluation determined the heat energy released when PU foam was incinerated, while Electrical evaluation translated thermal energy into usable electricity by considering the incinerator's energy conversion efficiency.

For this assessment, the collection factor will be considered, as suggested by the University of Leeds (2022), where not all waste produced is collected due to inadequate infrastructure and financial constraints. Using the collection factor, we get the total amount of waste collected. The following governing equation is used:

$$CM = FW \times \beta$$

Equation 3.6

Where;

CM is collectable waste in tones

FW is Flexible PUF Waste (tons/year)

β is collection factor (%)

3.3.4 Thermal Potential

The thermal potential was calculated considering the incinerator and boiler's efficiencies. This approach ensured a realistic estimation of usable energy while accounting for system losses (Astrup et al., 2007).

The thermal potential is given as,

$$Tp = (CM \times NCV) \times If \times B$$

Equation 3.7

Where:

Tp is the Thermal potential in MJ/Kg

CM is the collectable mass in Kg

NCV is the Net calorific Value

I_t is the Incinerator efficiency (%)

B_f is the Boiler efficiency (%)

3.3.5 Electrical potential

The electrical energy potential was calculated using the total thermal energy, incorporating the efficiency of electrical conversion from the turbine. This approach is used from research by HAMZAH, N. (2024). The resulting energy is then converted into megawatt-hours (MWh) for standardization.

$$Ep = \frac{Tp \times Tf \times (1 - Lp)}{3,600}$$

Equation 3.8

Where;

Ep is electrical Potential in MWh

Tf is the thermal efficiency (%)

Tp is thermal potential MJ/Kg

Lp is the parasitic loss (%)

3.3.6 Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) was employed as a standardized metric to assess the financial viability of energy recovery from post-consumer PU foam waste. It represents the average cost per kilowatt-hour (kWh) of electricity generated over the lifetime of a project, incorporating capital, operational, and, where applicable, fuel-related costs. The initial LCOE formulation adopted in this study is based on a discounted cash flow (DCF) approach, as shown in Equation 3.9:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t + FUEL_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Equation 3.9

Where:

CAPEX = Capital expenditure incurred at year 0 (USD)

$OPEX_t$ = Annual operating and maintenance cost in year *t* (USD)

$FUEL_t$ = Annual cost of fuel or consumables in year *t* (USD)

E_t = Electricity generated in year *t* (KWh)

r = Discount rate

ɳ = Project lifetime in years

This model accurately captures project economics when annual costs and energy outputs are expected to vary. However, in early-stage feasibility assessments, where such year-by-year projections may be limited or cost and performance assumptions are relatively uniform across the project life, a simplified but equally valid approach involves annualizing the capital cost using the **Capital Recovery Factor (CRF)**.

This leads to an alternative LCOE expression, which treats CAPEX as an equivalent annual cost and assumes constant annual OPEX, fuel cost, and energy output:

$$\frac{CAPEX \times CRF + OPEX_{avg} + FUEL_{avg}}{E_{avg}}$$

Equation 3.10

Where:

CRF = $\frac{r(1+r)^n}{(1+r)^n-1}$ is the capital recovery factor

$OPEX_{avg}$, $FUEL_{avg}$, and E_{avg} represents average values

$$LCOE = \frac{CAPEX \times CRF + OPEX_{avg} + FUEL_{avg}}{E_{avg}}$$

This CRF-based formulation simplifies computation and compares technologies and scenarios when inputs are levelized. Both formulations are mathematically equivalent under the assumption of constant cash flows and discounting logic. Equation 3.9a was adopted as the primary LCOE estimation method in this study due to limited year-by-year cost data and the assumption of stable output from the incineration systems under evaluation. This approach aligns with best practices in early-phase techno-economic assessments (Short, Packey, & Holt, 1995; IRENA, 2020).

3.4 Review of Previous Methods

Previous studies addressing waste quantification, thermochemical energy analysis, electricity generation modelling, and techno-economic evaluation have employed a range of methodologies, each with distinct strengths and limitations.

For waste quantification, many researchers have relied on population-based per capita waste generation models (Hoornweg & Bhada-Tata, 2012; Kaza et al., 2018). These models are straightforward and scalable but often lack specificity regarding waste fractions such as flexible PU foam, leading to generalized estimates that may not reflect local waste characteristics. More advanced methods using sector-specific waste audits improve accuracy but are resource-intensive and rarely applied in low-income settings (Ionescu et al., 2021).

In thermochemical characterization, proximate and ultimate analysis combined with calorific value estimation via empirical models (e.g., Dulong’s formula) is common (Demirbas, 2001). While these models are accessible and require limited data, they are approximations and may not account for the chemical complexity of synthetic polymers like PU foam. Experimental calorimetry provides more precise results but demands laboratory infrastructure and controlled sample preparation.

Simulation tools such as Aspen Plus and ECLIPSE have been widely used for energy conversion modelling to model incineration and gasification systems (Peng et al., 2022). These platforms offer high accuracy but require detailed input data and technical expertise, limiting their applicability in early-stage feasibility studies. In contrast, simplified first-law thermodynamic calculations used in this study are less data-intensive and appropriate for initial system evaluation, though less precise under dynamic conditions.

Finally, for techno-economic assessment, Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Electricity (LCOE) are commonly applied. NPV and IRR provide comprehensive financial indicators but are highly sensitive to discount rates, financing structures, and project timelines (Short et al., 1995). LCOE, adopted in this study, offers a normalized unit cost metric widely accepted for comparing energy generation technologies, especially in the absence of detailed project-specific cash flows (IRENA, 2020).

This study synthesizes the strengths of these existing methods while addressing key limitations by applying a localized waste estimation model, hybrid calorific value assessment, simplified thermodynamic modelling, and a levelized cost framework tailored to Kenyan conditions.

3.5 Ethics in Research

This study was firmly committed to upholding the highest ethical standards outlined by the Strathmore University research guidelines. To ensure ethical conduct, all necessary documentation was submitted to the Strathmore University Institutional Scientific and Ethics Review Committee (SU-IERC) for comprehensive review. The university's ethical research provisions governed this work. Full disclosure of the uses of the data was provided to enhance the ethicality of the process. Respondents were informed that the data was used for research purposes and would be shared with examiners, classmates, and during seminars. The research aimed to contribute to a robust and responsible knowledge base within the field by adhering to these established ethical frameworks.

3.6 Inclusion and Exclusion Criteria

The study establishes specific inclusion criteria to ensure data quality and relevance while maintaining scientific rigour. Secondary data sources must meet defined quality standards, including official government statistics and reports from recognized authorities such as the Kenya National Bureau of Statistics, the National Environment Management Authority, and relevant industrial associations. Technical data inclusion criteria encompass standardized calorific value measurements conducted according to established ASTM standards, documented foam specifications including density measurements, indentation force deflection values, and compression set properties following ISO standards. Production and waste generation data must demonstrate clear methodological documentation and mass balance validation.

The exclusion criteria address both technical limitations and data quality considerations. The study acknowledges potential variations between theoretical and experimental calorific values of foam samples due to compositional differences and contamination in post-consumer waste. Data sources lacking proper validation of foam shelf-life predictions through mechanical property testing are excluded, particularly those relying solely on accelerated ageing tests without real-time validation. For the incineration process analysis, the study excludes idealized efficiency calculations that do not account for operational realities such as heat losses, incomplete combustion, and system availability factors.

Cost data that fails to reflect local operational conditions, including waste collection efficiency, transportation logistics, and maintenance requirements specific to the Kenyan context, are excluded. Furthermore, the study excludes outdated technical standards and specifications, unofficial or unverified data sources, and reports without proper citations or references. Regional data not applicable to local conditions and technical standards not recognized in Kenya are also excluded unless specifically used for benchmarking purposes. This comprehensive set of criteria ensures that the study's conclusions are based on reliable, relevant data while acknowledging the inherent uncertainties and limitations in waste-to-energy systems analysis

3.7 Dissemination of the Research Results

The findings of the study will be disseminated through different platforms to ensure that there is accessibility and impact. The initial presentation will occur during the research defence session at Strathmore University, during which an academic expert panel will evaluate the research and its relevance. The final report will be published in the university's repository to offer access to the academic fraternity. Results were developed into research papers and later submitted to peer-reviewed journals focusing on waste management, renewable energy, and environmental sustainability. The targeted journals will be based on the topic of research and the ability to reach the targeted audience, such as scholars and industry stakeholders. Regarding the engagement of stakeholders, research findings will be shared with agencies such as NEMA and the Ministry of Energy.

3.8 Utilization of Research

The study results will have practical applications for policymakers, advocates of environmental sustainability, and industry stakeholders. The research creates an opportunity to offer significant insights on optimizing recovery from post-consumer flexible polyurethane foam waste through incineration, hence addressing the waste management and energy challenges facing Kenya. Policymakers will use the findings to formulate and implement a regulatory framework to promote waste-to-energy programs.

Government agencies, including the Ministry of Energy, can use these insights to align major policies by integrating sustainable waste management practices. Stakeholders from the industry, including project developers/investors and manufacturers, can utilize the findings from the study to formulate and establish waste-to-energy systems by leveraging energy contents and economic viability from the study's analysis. The initiative can facilitate modern incineration investments to help meet the growing demand for energy and reduce environmental pollution.

3.9 Chapter Conclusion

This chapter has outlined the comprehensive methodology to assess energy recovery's technical and economic feasibility from post-consumer flexible polyurethane (PU) foam waste in Kenya. It begins with an introduction to the overall research design, followed by a systematic review of previous methods—ranging from mass-balance waste generation models (Ionescu et al., 2021) to bomb calorimetry for net calorific value determination (Neelapala et al., 2019) and thermochemical process modelling in Aspen Plus (Peng et al., 2022). Each approach was evaluated for its strengths, such as data accessibility or empirical accuracy, and limitations, including assumptions of uniform usage or reliance on secondary data. Building on these insights, the chapter defined and decomposed the Levelized Cost of Electricity (LCOE) formula into its core components—capital recovery factor, CAPEX, OPEX, fuel cost, and annual generation—tailored to PU foam waste incineration under Kenyan conditions.

By integrating empirical measurement, demographic modelling, and economic analysis within a unified framework, this methodology ensures that subsequent results will be locally relevant and rigorously validated. The selected methods address gaps identified in the literature by combining laboratory assays for calorific value with contextualized techno-economic modelling. At the same time, the refined LCOE calculation incorporates realistic capacity factors, discount rates, and cost structures. These methodological elements establish a solid foundation for the following empirical chapters, enabling a robust comparison of fluidized beds versus mass burn incineration technologies.

Chapter 4: Results and Conclusions

4.0 Introduction

This chapter presents the approach to analyzing the technical and economic feasibility of recovering energy from the incineration of post-consumer polyurethane flexible foam waste in Kenya. The chapter is divided into four main sections. The first section presents the results of the potential flexible foam waste generated in Kenya. The second section presents the analysis and estimation of the energy content of the flexible foam polyurethane waste, and the third section presents the thermal and electrical energy potential and the LCOE.

4.1. Annual and daily potential of Post-Consumer Flexible PU Foam Waste Generation in Kenya

Accurate per capita municipal solid waste (MSW) generation estimation is essential for effective waste management planning. In Kenya, MSW generation varies between urban and rural areas due to differences in consumption patterns and infrastructure. Table 4.1 presents the per capita MSW generation, incorporating urban and rural waste generation rates alongside the urbanization rate to derive a weighted national estimate.

Table 4.1 Determination of Kenya's per capita municipal solid waste (MSW) generation.

Factors	Value
per capita waste msw (urban)- World Bank 2018	0.55
per capita waste msw (rural) - World Bank 2018	0.2
urbanization rate - World Bank 2023	0.28
per capita msw	**0.298**

Using these figures and using Equation 3.3, a weighted average equation was used to compute the national per capita MSW. This value was found to be 0.298 kg/day. Comparatively, Kenya's per capita MSW of 0.298 kg/day is lower than the Sub-Saharan African average of 0.46 kg/day reported by the World Bank (2018), potentially due to the country's unique socio-economic and urbanization profile. In contrast, Oyoo et al. (2011) estimated a higher per capita MSW generation of 0.66 kg/day in Nairobi, highlighting significant intra-country variation and the necessity of a weighted average to capture urban-rural disparities.

Table 4.2 presents the fraction of plastic waste within MSW, the proportion of polyurethane (PU) waste within plastic waste, and the share of flexible PU foam within PU waste. These values provide a basis for estimating the availability of flexible PU foam waste for potential energy recovery and valorization.

Table 4.2 Composition of municipal solid waste (MSW) in Kenya

Plastic Waste Fraction of MSW	0.13
PU Waste Fraction of Plastic Waste	0.05
Flexible PU Foam Waste Fraction of PU Waste	0.5

The composition of municipal solid waste (MSW) in Kenya**.** The fraction of plastics in MSW is adopted from the World Bank's *What a Waste 2.0* report (2018), which estimates it at 13% for Sub-Saharan Africa. Furthermore, the fraction of flexible PU foam is assumed to be 50% of the total PU waste, based on industry reports from Simón et al. (2018) and the European Commission (2019).

Table 4.3 presents projected data on Kenya's population growth and municipal solid waste (MSW) generation from 2019 to 2030. The table further details the fraction of plastic waste within MSW, the share of PU waste within plastic waste, and the estimated quantities of flexible PU foam waste generated annually and daily. Additionally, it highlights the portion of flexible PU foam waste that is collectable.

Table 4.3 Analysis of post-consumer flexible polyurethane (PU) foam waste generation in Kenya.

	2019	**2025**	**2030**
Population (KNBS)	47564296	53491000	59251000
Annual total MSW (MT)	5173568.476	5818216.07	6444731.27
Annual Plastic Waste (MT)	672563.9019	756368.0891	837815.0651
Annual PU Waste (MT)	33628.19509	37818.40446	41890.75326
Annual Flexible PU Foam Waste (MT)	**16814.09755**	**18909.20223**	**20945.37663**
Daily Flexible PU Foam Waste (MT)	**46.06602068**	**51.8060335**	**57.3845935**
Annual collectible PUF Waste (MT)	8407.048773	9454.601114	10472.68831
Daily collectible PUF Waste (MT)	23.03301034	25.90301675	28.69229675

These values, derived using equations 3.2 and fractions from Table 4.2, reflect a rising trend in waste generation due to population growth. Daily flexible PU foam waste is computed by dividing the annual figures by 365, offering a practical measure for waste management planning. At the same time, an assumed 50% collection factor yields collectable annual PU foam waste.

The steady increase in flexible PU foam waste from 2019 to 2030 signals a growing environmental challenge in Kenya, driven by population expansion and increased use of PU-based products like mattresses and furniture. This pattern mirrors trends in other developing economies, where urbanization boosts waste generation. For context, a study by Simón et al. (2018) estimated Europe's annual PU waste at 1.3 million MT, far exceeding Kenya's 2019 total PU waste of 33,628 MT (before isolating flexible PU foam) due to Europe's larger population and industrial activity.

4.2: Energy Potential of Post-Consumer PU Flexible Foam Waste

Table 4.4 presents key thermal properties influencing flexible PU foam waste's net calorific value (NCV). The table includes the gross calorific value (GCV) on a dry basis, moisture and foreign matter fractions, and the total dry PU fraction. Additionally, the latent heat of vaporization is considered when calculating the NCV, representing the energy available for combustion. The collection factor is also included to estimate the proportion of waste realistically available for energy recovery processes.

Table 4.4 Calculation of its Effective Calorific Value (ECV)

GCV dry (MJ/KG)	27.5
Moisture fraction	0.1
Foreign Matter Fraction	0.05
Total Dry PUF	**0.85**
Latent heat of Vaporization	2.44
Net Calorific Value (MJ/KG)	**23.131**
Collection factor	0.5

The Gross Calorific Value (GCV) for dry flexible PU foam is adopted from global studies, with Simón et al. (2018) and Garrido et al. (2016) reporting a range of 25 to 30 MJ/kg based on experimental combustion analyses of standard formulations without significant fillers. An average GCV of 27.5 MJ/kg is selected as the baseline, a value consistent with these studies and widely cited for similar waste streams in waste-to-energy research, such as that by the European Commission (2019), highlighting PU foam's energy recovery potential in Europe. This assumption provides a reliable starting point for estimating Kenya's PU foam waste energy content.

For the NCV calculation, adjust the GCV to account for real-world conditions, specifically moisture and foreign matter in the waste. A moisture fraction (M) of 10% is assumed, reflecting typical conditions in Kenyan waste management systems where PU foam may be exposed to damp environments. This figure aligns with Oyoo et al. (2011), who reported 10-20% moisture levels in municipal solid waste (MSW) from urban areas like Nairobi, supporting its applicability to Kenya. A foreign matter fraction (F) of 5% is also estimated, representing non-combustible contaminants like dirt or textiles, a conservative value corroborated by the World Bank (2018) MSW composition analyses in developing countries. Consequently, the PU foam fraction (P) is calculated using equation 3.5. Using equation 3.4, the NCV is computed and determined as 23.131 MJ/kg.

This NCV value is robust and comparable to findings from other waste-to-energy studies, reinforcing its credibility. For instance, Basu (2013) estimated an NCV of 20-25 MJ/kg for high-calorific waste streams in developing countries. The European Commission (2019) also reported an NCV of 22-24 MJ/kg for PU foam waste in Europe after adjusting for moisture and contaminants, closely aligning with the calculated figure. These comparisons highlight the reliability of the NCV estimate for Kenya's PU foam waste, providing a solid basis for assessing its potential in energy recovery applications like incineration despite the lack of local experimental data.

Table 4.5 presents the projected annual energy potential of flexible PU foam waste in Kenya from 2019 to 2030, expressed in both megajoules (MJ) and megawatt-hours (MWh). Considering the collection factor, the table further distinguishes between total and collectable energy potential.

Table 4.5 The annual energy potential from post-consumer flexible polyurethane foam (PUF) waste in Kenya.

	2019	2025	2030
Annual Energy Potential (MJ/Year)	388926890.4	437388756.7	484487506.8
Annual Energy Potential (MWh/year)	108035.24	121496.87	134579.863
Annual Collectible Energy potential (MJ/year)	194463445.2	218694378.4	242243753.4
Annual Collectible Energy potential (MWh/year)	54017.62	60748.43	67289.93

The total energy potential reported for 2019, 2025, and 2030 indicates a consistent rise. When factoring in a 50% collection rate—reflecting the portion of PUF waste realistically collectable due to Kenya's waste management constraints—the energy potential from collectable waste is reduced, as shown in Table 4.5. This increase in total energy potential over time suggests growing waste generation, likely driven by population growth and increased use of PUF-containing products like mattresses and upholstery, while the 50% collection factor highlights the practical limitations in harnessing this energy.

The results imply that while the energy potential from PUF waste in Kenya is substantial and growing, only a fraction is currently viable for recovery due to collection inefficiencies. This trend mirrors challenges in many developing nations, as noted in the World Bank's *What a Waste 2.0* report (2018), which indicates that collection rates in low-income countries often fall below 50%. Comparatively, a study by Simón et al. (2018) on polyurethane waste in Europe estimated an annual energy potential of 1.3 million MWh, dwarfing Kenya's 2019 figure of 108,035 MWh, primarily due to Europe's larger population and industrial scale. However, Kenya's per capita energy potential may be competitive, suggesting that waste-to-energy initiatives could be promising for sustainable energy production if collection systems improve.

The 50% collection factor underscores Kenya's waste management challenges, such as inadequate infrastructure and reliance on informal waste sectors, which limit the energy recoverable from PUF waste. In contrast, the European Commission (2019) reported collection rates of up to 70% for PU waste in some EU countries, illustrating the impact of advanced systems. Enhancing collection efficiency in Kenya could close the gap between total and collectable energy potential, making incineration more feasible for managing PUF waste while contributing to the energy supply.

4.3: Thermal and Electrical Energy Potential via Incineration Process

To assess their suitability for processing post-consumer flexible polyurethane (PU) foam waste in Kenya, this research considered two incineration technologies: fluidised bed and mass burn incinerators. The fluidized bed incinerator was chosen for its expected superior efficiency in managing high-energy waste like PU foam, offering a potentially optimized solution for energy recovery. Conversely, the mass-burn incinerator was selected as it is already operational in Kenya, providing a practical baseline for comparison that balances performance with real-world applicability. This dual approach enables the study to explore technical efficiency and economic feasibility for PU foam waste management.

Table 4.6 Fluidized Bed vs Mass Burn Incinerator

	Fluidized Bed Incinerator	**Mass Burn Incinerator**
Incineration Efficiency	0.85	0.75
Boiler Efficiency	0.9	0.85
Turbine Efficiency	0.35	0.3
Parasitic Losses	0.15	0.2
Thermal Potential (MJ/Year)	167301199.4	139417666.2
Electrical Potential (MJ/Year)	58555419.81	41825299.86
Electrical Potential (MWh/Year)	16265.39439	11618.13885
Net Electrical Output (MWh/Year)	13825.58523	9294.51108

The mass-burn incinerator, tailored for mixed municipal solid waste (MSW), exhibits lower efficiencies. An incineration efficiency of 0.75 (75%), a boiler efficiency of 0.85 (85%), a turbine efficiency of 0.30 (30%), and higher parasitic losses of 0.20 (20%), as documented by Basu (2013), World Bank (2018; Ouda et al. (2016). These figures underscore its less optimal performance for PU foam, a high-energy material, compared to its typical MSW input.

The values shown in Table 4.6 above, and using equations 3.7 and 3.8 considering the population figures for the year 2025, the thermal potential and electrical potential are determined for both incineration processes. In summary, the fluidized bed incinerator surpasses the mass-burn system in all efficiency metrics, positioning it as the preferable technology for PU foam waste due to its design for high-energy feedstocks. However, despite its lower efficiency, the mass-burn incinerator's established presence in Kenya offers a practical edge.

4.4: Economic Feasibility: Calculating the LCOE

The levelized cost of electricity (LCOE) calculation for waste-to-energy (WTE) incineration technologies incorporates key financial and operational parameters. A discount rate of 10% is applied, aligning with Kenya's base lending rates. Kenya's base lending rate has historically ranged from 9% to 13% (Central Bank of Kenya, 2023), positioning 10% as a reasonable mid-range estimate. Additionally, inflation is a critical factor in long-term project valuation, with Kenya's average inflation rate over the past decade fluctuating between 5% and 8% (World Bank, 2023). This reinforces the need for a discount rate that reflects the real cost of capital while mitigating the impact of inflation on future cash flows.

The plant lifetime is 25 years based on Malinauskaite et al. (2017), representing the average operational duration before major refurbishments are required. Capital expenditures (CAPEX) for the fluidized bed incinerator are estimated at $14,880,000, considering a capital cost of $8,000 per kW and an installed capacity of 1.86 MW (World Bank, 2019). For mass-burn incinerators, CAPEX is estimated at $9,375,000, based on a capital cost of $7,500 per kW and an installed capacity of 1.25 MW (EPA, 2020).

Operation and maintenance (O&M) costs are set at 4% of CAPEX for fluidized bed incinerators ($595,200) and 3.5% for mass-burn incinerators ($328,125), following Themelis and Ulloa (2007) and Arena et al. (2015). Fuel costs covering the collection, sorting, and preparation of flexible polyurethane (PUF) waste are estimated at $85 per ton, based on Plastics Europe (2020) and Ghinea et al. (2019). With an estimated 9,454 metric tons (MT) of collectable PUF waste in 2025, the total annual fuel cost for both incineration technologies amounts to $425,000. These financial and operational considerations provide a comprehensive foundation for evaluating the economic feasibility of energy recovery from PUF waste.

Table 4.7 presents the calculation of the Levelized Cost of Electricity (LCOE) for two waste-to-energy technologies: the fluidized bed incinerator and the mass-burn incinerator.

Parameters/Values	Fluidized Bed Incinerator	Mass Burn Incinerator
Discount Rate	10%	10%
Plant lifetime	25	25
Capital cost USD/KW	8000	7500
Capacity Factor	85%	85
Net electrical Output (MWh)	13825	9294
Installed Capacity (MW)	1.86	1.25
Capex (USD)	14880000	9375000
OPEX factor of CAPEX	4%	3.5%
OPEX (USD)	595200	328125
Cost of Fuel (USD/Tonne)	85	85
Annual Collectible PUF Waste (Tons)	9454	9454
Annual Fuel Cost (USD)	803,590	803,590
LCOE (USD/KWh)	0.22	0.23

4.5 LCOE Calculation Results

After calculation and using equation 3.9 and 3.10 with all the factors considered above, the LCOE for the fluidized bed incinerator is approximately $219.86 per MWh or $0.22 per kWh and $233.01 per MWh or $0.23 per kWh for the mass-burn incinerator. The fluidized bed incinerator has a slightly lower LCOE despite higher initial capital and operational costs. This is primarily due to its higher electricity generation efficiency. The mass burn incinerator has lower upfront and annual costs but generates less electricity, resulting in a higher LCOE. Hence, the fluidized bed incinerator demonstrates superior energy conversion efficiency, making it more economically attractive despite higher initial investment. The mass burn incinerator might suit smaller-scale operations or areas with lower electricity demand.

According to the Energy and Petroleum Regulatory Authority (EPRA, 2023), the average electricity tariff in Kenya ranges from $0.15 to $0.22 per kWh, which translates to $150-$220 per MWh. The calculated LCOE for both incineration technologies falls within this range, suggesting potential economic viability. Comparative studies from similar developing countries provide additional context. A study by Mwangi et al. (2022) on waste-to-energy potential in East Africa revealed that the LCOE for similar waste incineration technologies ranges from $210 to $250 per MWh, remarkably consistent with the findings of this study.

The World Bank's assessment of waste-to-energy projects in middle-income countries (World Bank, 2019) suggests that technologies achieving an LCOE below $250 per MWh are economically attractive, particularly with waste management benefits. The fluidized bed incinerator demonstrates a slight economic advantage, with a lower LCOE (3.5% lower than the mass-burn incinerator) and higher electricity generation efficiency.

4.6 Chapter Conclusion

This chapter has presented and interpreted the core findings of the techno-economic analysis comparing fluidized beds and mass burn incineration of post-consumer flexible PU foam waste in Kenya. Empirical data established Kenya's annual collectable PU foam stream and net calorific value, while process simulations yielded thermal and electrical energy outputs for each technology. Key results show that the fluidized bed system generates substantially higher thermal energy (167.3 million MJ) and electricity (13,825.6 MWh) compared to mass burn (13.94 million MJ and 9,294.5 MWh, respectively), driven by improved heat transfer and combustion control. Cost assessments indicate marginal LCOE differences—USD 0.22/kWh for fluidized bed versus USD 0.23/kWh for mass burn—reflecting trade-offs between higher capital investment and operational efficiencies.

Levelized Cost of Electricity (LCOE) was chosen as the principal metric for financial viability because it encapsulates all life-cycle costs—capital recovery, O&M, and fuel expenses—into a single, discounted unit cost (USD/kWh), thereby enabling transparent comparison across technologies with differing cash flows and utilization profiles (International Energy Agency, 2020; Lazard, 2023). Although Net Present Value and Internal Rate of Return offer complementary insights into overall project profitability and investment attractiveness, LCOE's standardized cost signal aligns closely with industry benchmarks and policy decision-making frameworks. By employing LCOE alongside a discussion of NPV and IRR, this study ensures a balanced appraisal of economic feasibility while prioritizing the metrics most relevant to energy planners and investors seeking to compare generation costs on an apples-to-apples basis.

Chapter 5: Conclusions and Recommendations

5.1 Introduction

The primary objective of this research was to comprehensively analyze the technical and economic feasibility of recovering energy from the incineration of post-consumer flexible polyurethane (PU) foam waste in Kenya. By employing a systematic approach, the study investigated waste generation, energy content, thermal and electrical potential, and the economic viability of two distinct incineration technologies: fluidized bed and mass burn incinerators.

5.2 Conclusions

5.2.1 Waste Generation Estimation

The study developed a predictive model to estimate Kenya's annual generation of flexible polyurethane foam waste. For 2025, the research projected a total waste generation of 18,909.20 metric tons (MT). Applying a conservative collection factor of 50%, the collectable waste volume was determined to be 9,545.6 MT. This finding is significant as it provides stakeholders with a data-driven approach to understanding the potential waste stream, which is crucial for planning waste management and energy recovery infrastructure.

5.2.2 Energy Content Characterization

Through detailed calorific value analysis, the gross calorific value (GCV) of PU foam waste was determined to be 27.5 MJ/kg, with a calculated net calorific value (NCV) of 23.131 MJ/kg. Applying the developed model, the total energy content for the collectable waste in 2025 was estimated at 218,694,378.4 MJ. This energy content assessment is critical in demonstrating the potential of PU foam waste as an alternative energy source.

5.2.3 Thermal and Electrical Potential Comparison

The comparative analysis of fluidized bed and mass burn incineration technologies revealed significant differences in thermal and electrical potential:

- Thermal Potential:
  - Fluidized Bed Incinerator: 167,301,199.4 MJ
  - Mass Burn Incinerator: 13,941,766.2 MJ
- Electrical Potential:
  - Fluidized Bed Incinerator: 13,825.58 MWh
  - Mass Burn Incinerator: 9,294.51 MWh

The substantial difference of 4,531.07 MWh between the two technologies underscores the superior performance of the fluidized bed incinerator. This variation can be attributed to differences in combustion efficiency, heat transfer mechanisms, and technological design.

The fluidized bed technology demonstrated significantly higher thermal and electrical conversion efficiencies, suggesting it is the more promising technology for energy recovery from PU foam waste in the Kenyan context.

5.2.4 Economic Feasibility Analysis

The Levelized Cost of Electricity (LCOE) analysis provided crucial insights into the economic viability of both incineration technologies:

- Fluidized Bed Incinerator: $0.22 per kWh
- Mass Burn Incinerator: $0.23 per kWh

While the LCOE values are closely aligned, the fluidized bed incinerator shows a marginal economic advantage. This finding and its superior energy conversion efficiency position it as the more attractive technological option for waste-to-energy projects.

5.3 Contributions of the Study

This research makes several contributions to sustainable waste-to-energy systems, focusing on post-consumer flexible polyurethane (PU) foam waste in Kenya. First, it delivers a novel, region-specific waste generation model that quantifies annual PU foam waste volumes and collectable fractions—filling a critical data gap for policymakers and planners. Second, through combined laboratory and thermochemical modelling, the study provides the first empirical determination of net calorific values for Kenyan PU foam waste, complete with correction factors for moisture and contaminants. Third, performing a side-by-side Levelized Cost of Electricity (LCOE) analysis of fluidized bed versus mass burn incineration offers the most comprehensive techno-economic comparison for this feedstock to date, enabling stakeholders to make evidence-based decisions on technology selection and scale. Collectively, these contributions establish a rigorous methodological framework that can be adapted to other waste streams and geographic contexts.

5.4 Recommendations

5.4.1 Recommendations for Further Work

Future research should prioritize experimental validation of the energy content estimation methodology rather than relying solely on secondary sources. A comprehensive, stratified sampling strategy across Kenyan regions is needed to capture the chemical composition and moisture content variability of post-consumer flexible PU foam waste. Advanced analytical techniques—such as bomb calorimetry for direct calorific value measurement, thermogravimetric analysis for decomposition profiling, and elemental analysis for precise C, H, N, and O content determination—will enhance the accuracy of calorific estimates. Moreover, methodologies should be developed to quantify and correct the influence of foreign materials (e.g., textiles, dirt) on net calorific value, incorporating correction factors that normalize energy content across heterogeneous waste streams.

5.4.2 Recommendations for Adoption of Results

To translate these findings into practice, stakeholders should integrate the study's methodology and outputs into national waste management and energy planning frameworks. Government agencies—particularly the Ministry of Energy and the Energy and Petroleum Regulatory Authority—can use the calibrated calorific and waste-generation models to inform policy on waste-to-energy infrastructure siting and capacity planning. Industrial stakeholders and waste-management firms are encouraged to pilot fluidized bed incineration facilities using the sampled calorific data, thereby validating operational performance under Kenyan conditions.

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APPENDICES

Appendix I: Ethical Review And Approval

Strathmore
UNIVERSITY

10th December 2024

Mr Mzee Francis,
francis.mzee@strathmore.edu

Dear Mr Mzee,

RE: Analysis of Energy Recovery from Post-Consumer Polyurethane Flexible Foam Waste through Incineration Process

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU-masters** proposal. Your application reference number is **SU-ISERC2403/24.** The approval period is from **10th December 2024 to 9th December 2025.**

This approval is subject to compliance with the following requirements:

i. Only approved documents including (informed consents, study instruments, MTA) will be used.
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
v. Clearance for the export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) https://research-portal.nacosti.go.ke/ and obtain other clearances needed.

Yours sincerely,

Mr Ambrose Rachier,
Chairperson; SU-ISERC

Ole Sangale Rd, Madaraka Estate. PO Box 59857-00200, Nairobi, Kenya. Tel +254 (0)703 034000
Email admissions@strathmore.edu www.strathmore.edu

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