Investigating the co-processing of municipal solid waste as an alternative fuel in cement production

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PREFACE AND ACKNOWLEDGMENTS

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ABSTRACT

Pillar 1 of the National Waste Management Strategy, which focuses on waste minimisation, has a focus area aimed at *"Advancing Waste as a Resource"* that, amongst others, aims to expand the use of refuse-derived fuel (RDF) in South Africa. This research aims to investigate the co-processing of municipal solid waste (MSW) as an alternative fuel in cement production in South Africa. Unlike the conventional method in cement rotary kilns, that primarily depends on coal as a fuel source, RDF from MSW can facilitate the transition toward a circular economy. The transition from a primarily coal-based energy source to RDF has the advantage of diverting MSW from landfill and reducing carbon dioxide emissions.

The experimental design was modelled from a combination of mechanical treatment and bio-drying of waste. To develop a coal substitute in the form of RDF, a mechanical treatment process involved a series of downsizing the waste by way of shredding and granulating, while magnetic separation was done to eliminate ferrous metals. Furthermore, three sets of waste samples were tested. The samples had biogenic MSW, which comprises paper and synthetic carbon MSW which comprises plastic. The samples were dried and sampled in a controlled laboratory to examine the physio-chemical properties of RDF, utilising the proximate analysis of the ASTM D7582 standard. The results proved that at 28.15 MJ/kg, a 50% biogenic to 50% synthetic carbon source ratio will meet and exceed the operational efficiency requirements of heating the pre-calciner at 14 MJ/kg. Furthermore, the ratio meets the technical efficiency criteria with less than 0.3% chlorine, and less than 3% moisture. The sample emits a CO_2 factor of 72 CO_2 tonnes/TJ compared to 94.1 CO_2 tonnes/TJ emitted by coal.

Although RDF was considered a suitable alternative fuel for cement production, based on technical and efficiency aspects, challenges may exist in terms of operational/practical implementation. The research, thus, explored the perceptions of 22 specialists involved in the cement manufacturing process to determine potential opportunities and challenges. Perceived opportunities included increased kiln efficiency, improved innovation, reduced cost of cement production, reduced cost of waste management, reduced greenhouse gas emissions, promotion of landfill diversion, promotion of environmental sustainability, reduced fossil fuel (coal) dependency, pollution prevention, and bringing about positive changes in the public perception of waste. On the other hand, perceived challenges included concerns around incompatibility of cement kilns, cost of infrastructure, cost of waste (once it has value), emissions from burning of MSW, as well as difficulties in licensing.

Keywords: *Refuse derived fuel, RDF, municipal solid waste, MSW, cement processing*

ABBREVIATIONS AND ACRONYMS

AF	Alternative Fuels
AFR	Alternative fuel and raw material
ASTM	American Society for Testing & Materials
^{o}C	Degree Celsius
C	Carbon
CDM	Clean Development Mechanism
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq ($_{T/TJ)}$	Carbon dioxide equivalent tons per tera joule
CV	Calorific Value
DEA	Department of Environmental Affairs (now DFFE)
DEFF	Department of Environment, Forestry and Fisheries (now DFFE)
DFFE	Department of Forestry, Fisheries and Environment
Dioxins	A term/abbreviation for polychlorinated dibenzodioxins and polychlorinated dibenzofurans (see also PCDD/Fs)
DoE	Department of Energy
EF_{-C02}	Emissions Factor of carbon dioxide equivalent
EPA	United States Environmental Protection Agency
EU	European Union
GHG	Green House Gases
GWP	Global Warming Potential
IPPC	Inter-Government Panel on Climate Change

IRP	Integrated Resource Plan
ISO	International Organization for Standards
kcal	Kilocalorie (1 kcal = 4.19 kJ)
kg	Kilogramme (1 kg = 1000 g)
kJ	Kilojoules (1 kJ = 0.24 kcal)
LDPE	Low density polyethylene
LHV	Lower Heat Value
MBT	Material Biological Treatment
MRF	Material Recovery Facility
MSW	Municipal solid waste
MWh	Mega watt hours
NEM: WA	National Environmental Management: Waste Act
NOx	Nitrogen oxides ($NO+NO_2$)
Nm^3	Normal cubic metre (101.3 kPa, 273 K)
NWMS	National Waste Management Strategy
NEMAQA	National Environmental Air Quality Act
REIPP	Renewable Energy Independent Power Producer
RDF	Refuse Derived Fuel
SDG	Sustainable Development Goals
SO_2	Sulphur dioxide
UNFCC	United Nations Framework Convention on Climate Change
WtE	Waste-to-energy

KEY DEFINITIONS

Alternative Fuel

Alternative fuel (or AF) is defined as combustible non-fossil solid fuel, waste, and by-products to a significant calorific value (Grammelis *et al.*, 2021)

Alternative Fuels and Raw Materials (AFR)

General and hazardous wastes which are used to substitute conventional or primary fossil fuels and virgin materials in cement kilns and other industrial processes (also referred to as ‘Alternative fuels and resources’, ‘secondary materials’, ‘refuse derived fuel’, or ‘solid recovered fuel’ (GN. 777 of July 2009, National Policy on Thermal Treatment of General and Hazardous Waste).

Co-processing

The utilisation of alternative fuels and raw materials in industrial processes for energy or resource recovery and reduction in the use of conventional fuels or raw materials through substitution (GN. 777 of July 2009, National Policy on Thermal Treatment of General and Hazardous Waste).

Dioxins (also referred to as PCDD)

Dioxins are a group of highly toxic chemical compounds that harm health. They can cause problems with reproduction, development, and the immune system. They can also disrupt hormones and lead to cancer (Aremu, 2021).

Disposal

The burial, deposit, discharge, abandoning, dumping, placing, or release of any waste into or onto, any land (National Environmental Management: Waste Act 59 of 2008).

Domestic waste

Waste, excluding hazardous waste, emanates from premises used wholly or mainly for residential, educational, health care, sport or recreation purposes (National Environmental Management: Waste Act 59 of 2008).

Fossil fuel

Non-renewable, decayed organic materials that over time have formed geological deposits or carbon, such as oil, natural gas and coal, are combustible and release energy through burning (GN. 777 of July 2009, National Policy on Thermal Treatment of General and Hazardous Waste).

Greenhouse Gas (GHG)

Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation, and includes carbon dioxide, methane and nitrous oxide (GN. 777 of July 2009, National Policy on Thermal Treatment of General and Hazardous Waste).

Kyoto protocol

International agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties by setting internationally binding emission reduction targets. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005 (United Nations Framework Convention on Climate Change, 2019).

Landfill

A system of trash and garbage disposal in which the waste is buried between layers of earth to build up low-lying land (Merriam-Webster, 1903). Note: Also refer to the NEMWA definition of “waste disposal facility)

Municipal Solid Waste

Municipal Solid Waste (or MSW) more commonly known as waste, trash or garbage—consists of everyday items we use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, schools, hospitals, and businesses (EPA, 2019). This is also referred to as “domestic waste” in the South African context.

Proximate Analysis

The Proximate Analysis includes Moisture, Ash, Volatile Matter and Fixed Carbon content. They are determined by means of gravimetric tests, both direct and indirect, that allow their calculation (EPA 2019).

Recovery

The controlled extraction of a material or the retrieval of energy from waste to produce a product (National Environmental Management Waste Act, Act 59 of 2008).

Recycle

A process where waste is reclaimed for further use, which process involves the separation of waste from a waste stream for further use and the processing of that separated material as a product or raw material (National Environmental Management Waste Act, Act 59 of 2008).

Refuse Derived Fuel (RDF)

Refuse Derived Fuel (or RDF) are the non-hazardous but combustible portion of Municipal Solid Waste that can be utilised as alternative fuel in waste-to-energy technologies (Hemidat *et al*., 2019).

Thermal Treatment

Incineration, co-processing and other high-temperature treatment of general and hazardous waste (GN. 777 of July 2009, National Policy on Thermal Treatment of General and Hazardous Waste).

Ultimate Analysis

Ultimate analysis of coal and coke is defined in ASTM D3176 as the determination of the carbon, hydrogen, nitrogen, and sulphur in the material, as found in the gaseous products of its complete combustion, the determination of ash in the material as a whole, and the estimation of oxygen by difference (ASTM, 2014).

Waste

(a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste. (National Environmental Management: Waste Act, Act 59 of 2008, as amended in 2014).

Waste disposal facility

Any site or premise used for the accumulation of waste with the purpose of disposing of waste at that site or on that premise (National Environmental Management: Waste Act, Act 59 of 2008).

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CHAPTER 1 INTRODUCTION

1.1 Background

Good decision-making about how to sustainably manage waste is one of humanity's most critical contributions to reducing the impacts of waste on the natural environment (Wilson *et al.,* 2015). Cities worldwide generate about 1.3 billion tonnes of municipal solid waste (MSW) annually (Gamesby, 2020), expected to increase to 2.2 billion tonnes by 2025. In Africa, MSW is expected to grow to 244 million tonnes annually by 2025 (Hemidat *et al*., 2019).

Around the world, solid waste is handled differently. However, most countries' standard management methods include solid waste landfilling, composting, recycling, and incineration. In Africa, landfilling is still the most generally used method for waste disposal. The downside of landfilling MSW is the consequent greenhouse gas (GHG) emissions, a primary agent linked to climate change. Findings by Sagala *et al*. (2018) estimated that 1.6 billion tonnes of carbon dioxide–equivalents (CO_2-eq) GHG emissions were generated from MSW handling and disposal in 2016, which accounts for about 5% of global GHG emissions. If the *status quo* is maintained, solid waste-related emissions are anticipated to increase to 2.6 billion tonnes of CO_2-equivalents by 2050 (Cayuela *et al.,* 2019).

On a more positive note, there has been a growing worldwide sense of urgency in tackling climate change. The United Nations Sustainable Development Goals (SDGs) specifically address climate change as part of SDG 13, which aims to *“Take urgent action to combat climate change and its impacts”* (Cappocci, 2022). In 2016, 196 countries came together to limit global warming to well below 2 ˚C, preferably to 1.5 ˚C, compared to pre-industrial levels (Böhringer *et al.,* 2021). The Paris Agreement on climate change sets a goal of reducing global GHG emissions by assigning emission reduction goals to each signatory country and encouraging the development of green technologies. Waste management plays a role in this process by reducing emissions from the waste sector. This can be done through reducing the amount of waste generated, or by diverting waste from landfill sites through reuse, recycling, composting, and energy recovery from waste. These activities may assist in reducing GHG emissions and contribute to the aims of the Paris Agreement.

It is, therefore, not surprising that research, innovation and technologies towards diverting waste away from landfill sites have attracted increased attention over the past twenty years (Lowitt, 2020). This research specifically focuses on one of these areas, namely energy recovery from waste, or waste-to-energy, by focusing on the use of municipal solid waste (or MSW) as a refuse-derived fuel (RDF) in cement manufacturing. Refuse-derived fuel (or RDF) is a kind of alternative solid fuel derived from municipal or industrial solid wastes, recyclable materials such as plastic, glass, or after decomposing burnable hard-to-recycle materials (Kara *et al*., 2011). An area of interest in the beneficial use of waste is the co-processing of RDF in cement processing. Cement manufacturing has been selected as one of the most environmentally challenged industries and a potential destination for RDF to replace a portion of conventional fossil fuels with less energy-intensive fuel (Reza *et al*., 2013).

1.2 Problem statement and rationale for the study

The waste management hierarchy, where waste is diverted from landfill disposal towards more preferred alternatives (such as reuse, recycling and recovery), is entrenched in the South African legal framework for waste management. Pillar 1 of the National Waste Management Strategy (NWMS) (Chitaka *et al*., 2020), which focuses on waste minimisation, has a focus area aimed at *"Advancing Waste as a Resource"* that, amongst others, aims to expand the use of refuse-derived fuel (RDF) in South Africa. Refused-derived fuel (RDF) is a fuel derived from household, industrial and commercial waste that typically has an energy content of between 10 and 14 MJ/kg. Generally, RDF is used as an alternative to coal in industrial and utility boilers for electricity, and for process steam generation. RDF can also be used as a fuel in cement kilns for the production of cement and in other thermal usages. By utilising RDF, utilities and industries can both reduce their reliance on non-renewable resources (such as coal) and decrease the amount of general waste sent to landfill sites. The South African policy context is in favour of the co-processing of RDF. The National Policy on Thermal Treatment of General and Hazardous Waste (GN. 777 of July 2009) allows for the co-processing of alternative fuels and raw materials (AFRs), which includes RDF, in cement production (Buyelwa, 2009).

Cement manufacturing is one of the most energy-intensive industrial processes, mainly because most cement kilns are coal-powered. The cement manufacturing process, therefore, makes a notable contribution to GHG emissions (Herrero & Vilella*,* 2018), 149. (Wojtacha-Rychter *et al.,* 2021) Research by Psomopoulos & Themelis (2016) shows that the fuel mix used by the cement industry is carbon-intensive and contributes approximately 5% to global CO_2 emissions. These findings prove the need to reduce the dependency on coal in cement production.

RDF has been proven to be a resource used as energy, especially in cement kilns, without compromising clinker quality (Haas & Webber, 2010). The cement industry estimates that up to 20% of the heat from RDF could supply the load of a cement kiln, and the cement kiln could also burn other wastes, such as tyres/rubber crumbs, at the same time (Gendebien *et al*., 2003). Regarding the RDF to coal ratio in cement co-processing, Punin *et al.* (2023) argue that RDF could replace significant quantities of coal used in cement kilns. Azam *et al.* (2019) estimate that up to a 30 % ratio of RDF to coal is desired for density, favourable low moisture, and higher heat value.

Currently, there has been little scholarly analysis on the adoption of MSW as RDF in South Africa, both in the contexts of waste-to-energy and cement production. Based on research findings by the National Centre for Resource Recovery (NCRR, 1980), The International Panel on Climate Change the European Union's Waste Framework Directive (1975) Duquennoi *et al.* (2022), and work by Hemidat *et al*. (2019), reliable and traceable data is available on the efficiency of RDF as an alternative fuel. However, it is essential to note that RDF production and application are not a one size fits all solution (Moodley, 2014). From region to region, waste classification differs; thus, it is imperative to evaluate South African waste streams and their potential for RDF production.

This research, therefore, aims to investigate the co-processing of MSW as an alternative fuel (or RDF) in cement production. This research aims to contribute to the existing efforts to reduce the reliance on coal, and lower GHG emissions from cement manufacturing. The experimental design includes substituting the desirable properties of coal by blending MSW combinations to supplement or replace coal as a fuel for cement manufacturing purposes.

1.3 Research aim and objectives

This research aims to investigate the co-processing of municipal solid waste (MSW) as an alternative fuel in cement production in South Africa.

In line with the research aim, the following research objectives were pursued:

Research objective 1: To analyse the physio-chemical properties of Refuse Derived Fuel (RDF) for the purposes of cement production;

Research objective 2: To optimise the carbon benefit of RDF as a fuel in cement processing; and

Research objective 3: To investigate the opportunities and challenges for using MSW as RDF in cement production.

1.4 Scope of the research

This research focuses on the co-processing of municipal solid waste (MSW) as an alternative fuel for cement production. Although MSW may be used as an alternative fuel in other industrial processes, no other processes apart from cement production were included in this research.

The MSW included in this research consisted of non-hazardous plastic and paper (at three different ratios) only. Although other MSW streams may have the potential to provide energy for recovery processes, this research only focused on plastic (to represent synthetic carbon) and paper (to represent biogenic carbon) as a source of RDF for cement manufacturing, because the Interwaste Environmental Management service RDF plant, which is the RDF plant that the researcher conducted his research on, does not have a Material Recovery Facility (MRF) to handle unsorted and mixed MSW.

In this research, MSW was not used or tested in a cement kiln during actual cement production. However, in a controlled laboratory set up, different MSW ratios were tested for their physical and chemical properties to supplement/replace coal to achieve optimal conditions. Physical properties such as ash, volatile matter, and moisture content were tested using proximate analysis, and chemical properties and elements such as calorific value, chlorine, fixed carbon, sulphur and hydrogen were tested using the ultimate analysis, using ASTM D5865 and ASTM-D7582. No other test methods were employed to analyse the physio-chemical properties of the MSW.

As part of the research scope, the amount of carbon dioxide (CO_2) which would be emitted when using RDF in cement manufacturing is estimated (calculated). The researcher acknowledges that the co-processing of RDF in thermal processes during cement manufacturing may produce other emissions such as particulate matter (PM), sulphur dioxide, oxides of nitrogen, hydrogen chloride/fluoride, heavy metals, and dioxins and furans (PCDD/Fs). These emissions were not included in the scope of the research.

Furthermore, the adoption of RDF as a fuel in cement production is influenced by several other options such as public perception and government policy (Burchman *et al*, 2019). Typically, when alternatives fuels are researched, much emphasis is given to the technical and environmental contribution. Given that waste management starts at household level, it becomes imperative to give a holistic evaluation on the adoption of RDF in South Africa by factoring the human behaviour contribution (Genon *et al*., 2008). To achieve this goal, the opportunities and challenges related to using MSW as an RDF in cement production were researched based on available literature and supplemented by survey responses from twenty-two (22) industry experts from the cement manufacturing sector in South Africa.

Survey participant responses are limited to *perceived* opportunities and challenges and may, in certain instances, not provide an accurate reflection of the actual opportunities and challenges. Industry experts were representative of five of the ten cement manufacturers in South Africa as published by the (Global Cement Report of 2019 (Cemnet, 2019), and included AfriSam, PPC, Lafarge (Geocycle), and Natal Portland Cement (Intercement). The research was conducted between January 2022 and November 2023.

1.5 Assumptions and limitations

The limitations related to the research scope need to be considered when reading the research findings. The following assumptions are applicable to the research scope:

- Municipal Solid Waste (MSW) can be used as an alternative fuel in the form of Refuse Derived Fuel (RDF);
- RDF can efficiently substitute coal as a fuel in cement production by meeting the minimum heat value and chemical requirements of the kiln; and
- RDF can significantly reduce GHG emissions in cement production.

1.6 The potential contribution of the research

This research aims to promote the utilisation of MSW as an alternative fuel in cement production. In doing so, the research aims to reduce the amount of waste disposed to landfills and reduce the reliance of cement manufacturing on coal-based energy. This research may play a role in contributing to SDG 7 (affordable energy), SDG 9 (industry innovation), SDG 12 (responsible consumption and production), and SDG 13 (climate action).

The research further works towards the goals of the National Waste Management Strategy of South African, which focuses on implementing the waste management hierarchy, through energy recovery from waste. In the academic domain, the research contributes to further research and provides traceable findings to the limited publications on the use of MSW as an alternative fuel (RDF) in cement manufacturing, especially in South Africa and Africa at large.

1.7 Structure and outline of the dissertation

The dissertation consists of five chapters, where Chapter 1 sheds light on the global and local waste management and energy challenges. The problem statement details the motivation behind conducting this study, the chapter further explains the aims and objectives, as well as the scope and limitations. The second chapter provides the literature review, which gives an overview of time series data, giving the history and recognising the merits of past researchers, and the methods used to make quantifiable and traceable conclusions, the challenges and opportunities associated with utilising refuse-derived fuels are highlighted in this chapter. Chapter 3 provides the research methodology and outlines the research design employed to address the research problem and objectives. The chapter explains the methods utilised to measure the physio-chemical properties and classification which informs RDF properties. Chapter 4 provides the analysis, interpretation and discussion of the research findings linked to the research objectives (provided in Chapter 1). Finally, Chapter 5 concludes the findings of the research and makes recommendations, where applicable.

1.8 Chapter summary

This chapter introduced the background, problem statement and justification of this research. A brief background of how sustainable waste management and the use of municipal solid waste as a fuel in cement production can be linked to remediate the operational and environmental bottlenecks hindering both sectors. The aims and objectives as well as the potential contribution of the research were explained to provide the reader with an appreciation of the reasons behind the chosen research topic. The following chapter presents the literature review, which provides context to the dissertation.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Researchers have adopted a process-oriented perspective on major sources of greenhouse gas emissions, revealing how the world has become more conscious of its carbon footprint. Municipal Solid Waste (MSW) landfills in the United States are the third-largest source of human-related methane emissions (Bruggers *et al.,* 2021). According to studies by Kristanto & Koven (2019) and Eurostat (2020), waste disposal is the fourth largest source of emissions, accounting for 3 to 4% of total global greenhouse gases (GHGs) since 2017.

Approximately 2.01 billion tonnes of solid waste are generated, globally, per year, with population growth and urbanisation contributing to the rapid generation of waste. According to a study by the World Bank in 2016) waste generation is expected to increase to 3.40 billion tonnes in 2050 (World Bank, 2018). Most municipalities in developed countries have developed and implemented various waste management schemes or programmes to address waste management issues. The European Union (EU) is among the global leaders in developing and implementing waste management policies (Allevi *et al*., 2021).

However, unlike the EU, the majority of African countries lag in municipal solid waste management. African municipalities face five distinct problems: inadequate service coverage, operational inefficiencies of services, limited utilisation of recycling activities, inadequate management of non-industrial hazardous waste, and inadequate landfill disposal (Zurbrugg & Schertenleib, 1998). Although these challenges are realised within the South African context, and the National Waste Management Strategy (NWMS) aims at diverting waste away from landfills, however, the most frequently applied waste management option for MSW is still disposal by landfill (Moodley, 2014). Considering the impacts of landfilling on the environment, we are urged to actively seek to implement alternatives to landfilling.

In this chapter, the researcher aims to communicate the progress made in applying MSW in refuse-derived fuels (RDF) worldwide, as an alternative energy source, and an alternative to landfilling. The literature review provides the context and background to the research and justifies the selected research methods. The literature included several research papers by local and international scholars published in peer-reviewed journals, studies published by research institutions and private sector organisations, as well as applicable legislative documents.

2.2 The global energy crisis

Apart from the waste management crisis, world population growth, an escalating increase in demand, and continued dependence on fossil-based fuels for energy generation have caused a global energy crisis (Wang *et al.*, 2021). The availability of energy has transformed the course of humanity over the last few centuries and has prompted more and more innovations that keep increasing the global energy demand. Figure 2-1 shows time series data between 1800 to 2021, indicating how drastically the energy demand has changed from approximately 80 000 Tera-watt hours (TWh) in the 1980s to over 160 000 TWh in 2021 with sources of energy mainly being coal-, oil- and gas-based.

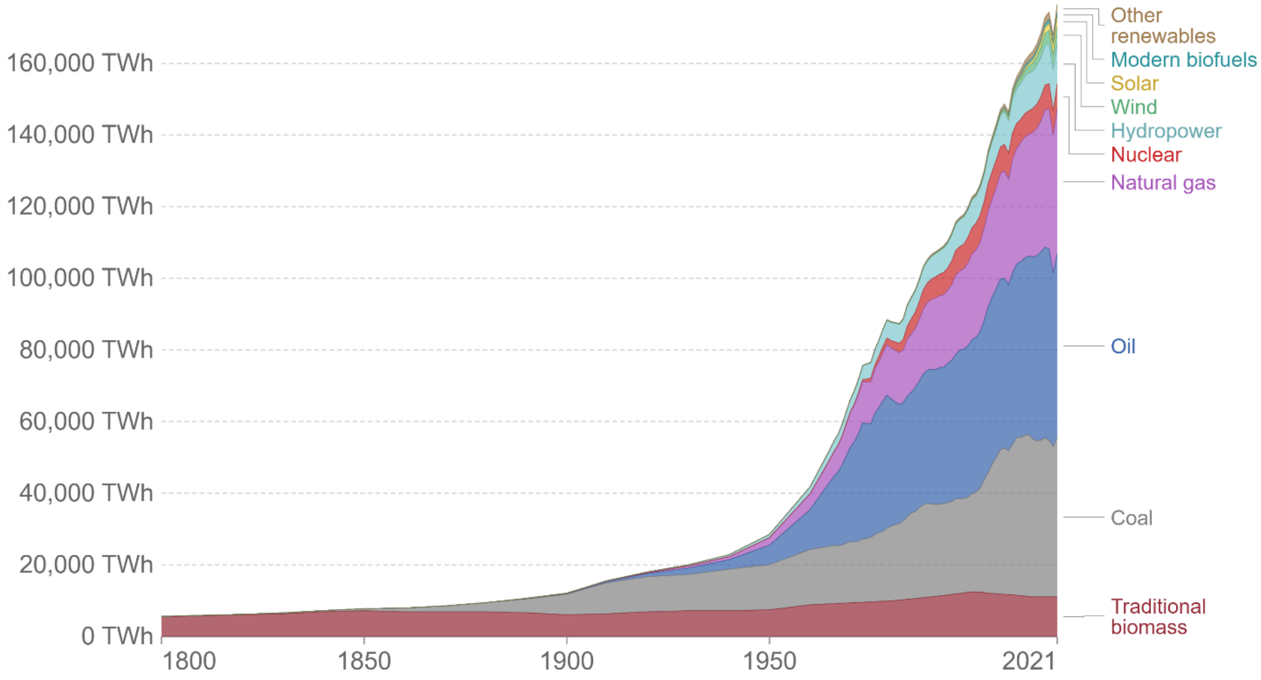

Figure 2-1:Global primary energy consumption by source from 1800 to 2021 (Smil, 2017)

Figure 2-1 indicates how much the world relies on fossil fuels to meet its energy needs. The gap that still exists between the generation of renewable energy and the use of fossil fuels for energy generation indicates the work and investments necessary to reduce reliance on non-renewable energy sources, such as coal, oil, and gas.

The increase in coal usage (as opposed to renewable energy sources) results in higher greenhouse gas (GHG) concentration levels. GHGs have been directly linked to adverse effects on air quality and are a known driver of climate change (Coyle *et al.*, 2014). Globally, countries around the world are implementing strategies to move towards renewable energy sources, with a view of reducing pressure on non-renewable energy sources, while also reducing the resultant emissions related to energy generation. The International Renewable Energy Agency's Global Renewable Energy Roadmap includes several recommendations for incorporating waste-to-energy technologies into existing energy systems. The International Energy Agency's (IEA) Energy Technology Perspectives also puts forth a forward-looking analysis of the potential of waste-to-energy pathways in the energy mix. Additionally, countries like China, India, Germany, and the United States are all actively pursuing waste-to-energy strategies, either through national policies or incentivising private sector investment (Coyle *et al.*, 2014).

Nhleko *et al*. (2020) argue that the South African government must fast-track its efforts to provide credible and reliable electricity supply through diversified and decentralised generation strategies. To achieve solutions that can curb the South African high energy demand to the required scale and magnitude within a limited timeline, significant steps forward in the development and use of technology are needed (Coyle *et al*., 2014).

South Africa is a signatory to the Paris Agreement on Climate Change and has ratified the agreement. In line with the Intended Nationally Determined Contributions (INDCs) submitted to the United Nations Framework for Climate Change Commission (UNFCCC) in November 2016, South Africa’s emissions are expected to increase between 2016 and 2025, plateau and, from the year 2025, decline. The energy sector is a major source of these emissions.

The country has attempted to address the energy crisis by focusing on “energy transitioning” through the Integrated Resource Plan (IRP) and the Just Energy Transition Partnership. *Energy transition* is defined as a vision-led, unifying and place-based set of principles, processes, and practices that build economic and political power to shift from an extractive economy to a regenerative economy (Burchman *et al*, 2019). The IRP focuses on the addition of renewable energy generation capacity (22500 MW of solar and wind power), while the JETP aims to address the end-of-life decommissioning of a substantial amount of coal-fired generation capacity (about 11000 MW) by 2030 (Mantashe, 2019). While the focus on the shift from coal to renewables is in full force, the JETP ensures that the switch does not make fossil fuel jobs obsolete. In addition, the policy is based on a re-skilling framework to avoid ghost towns and migrations to where renewables are being erected.

2.2.1 The South African energy sector

In line with the planned capacity in the promulgated Integrated Resource Plan (2010 – 2030) and Section 34 of the Electricity Regulation Act (4 of 2006), the Minister of Energy determined (in 2019) that 39 730 MW of new energy generation capacity must be developed to meet the subsequent energy demand. Furthermore, the generation plan focused on having a more balanced energy mix, since the energy sector contributes nearly 80% of the country's total GHG emissions (Mantashe, 2019).

The IRP also reveals coal is projected as a significant source of electricity generation in South Africa in the foreseeable future, and that South Africa will still support coal-based energy as part of its energy mix. According to the SA Energy Sector Report (2016) & SA Energy Sector Report (2019), in 2016, approximately 77% of South Africa's primary energy needs were provided by coal (Mantashe, 2019)(Figure 2-2).

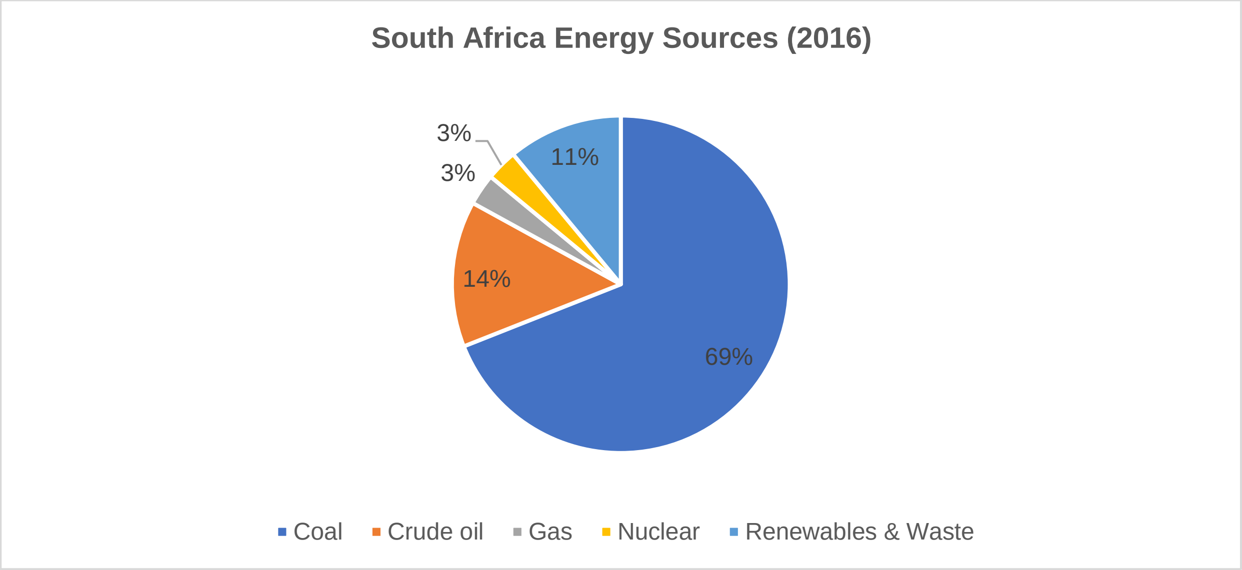

Figure 2-2: Total primary energy supply in 2016 (Adopted from: DoE Energy Balances, 2016)

The IRP indicates that reliance on coal is unlikely to change in the next two decades owing to the relative lack of suitable alternatives to coal as an energy source. However, some schools of thought by Todd *et al* (2021) appeal to the notion that South Africa must transition to a net-zero emissions future through abatement technologies and sustainable policy.

Similarly, the South African National Waste Management Strategy (2020) (NWMS) mentions the potential of waste-to-energy (WtE) as an alternative to landfilling. However, the NWMS also highlights the current challenge of limiting waste-to-energy companies. These challenges are said to be geographical and demographic constraints on the economies of scale needed to achieve commercially viable volumes that sustain waste generation. (Creecy, 2020). Thus, WtE is undoubtedly an innovation worth considering within the South African context.

2.3 Waste-to-energy (WtE)

According to the NWMS (DFFE, 2020), waste-to-energy (WtE) is *"the process of generating energy in the form of electricity and /or heat from the primary treatment of waste, or the processing of waste into a fuel source".* The earliest recorded WtE plant was built in Sweden in 1904 (Breeze, 2018). WtE technologies can convert the energy content of different types of waste into various forms of valuable energy, such as electricity which is generated by waste-to-energy power generators and distributed through local and national grid systems. Waste-to-energy systems ranges from incineration, gasification, and pyrolysis (Mathews *et al.,* 2000).

The following sub-sections will evaluate the use of municipal solid waste (MSW) in waste-to-energy systems, as well as the policy context, and the environmental, social and economic benefits of WtE projects.

2.3.1 Waste-to-energy (WtE) options

Figure 2-3 provides an outline of technological options of waste-to-energy (WtE) for effective management of municipal solid waste (Kumar & Samadder, 2017).

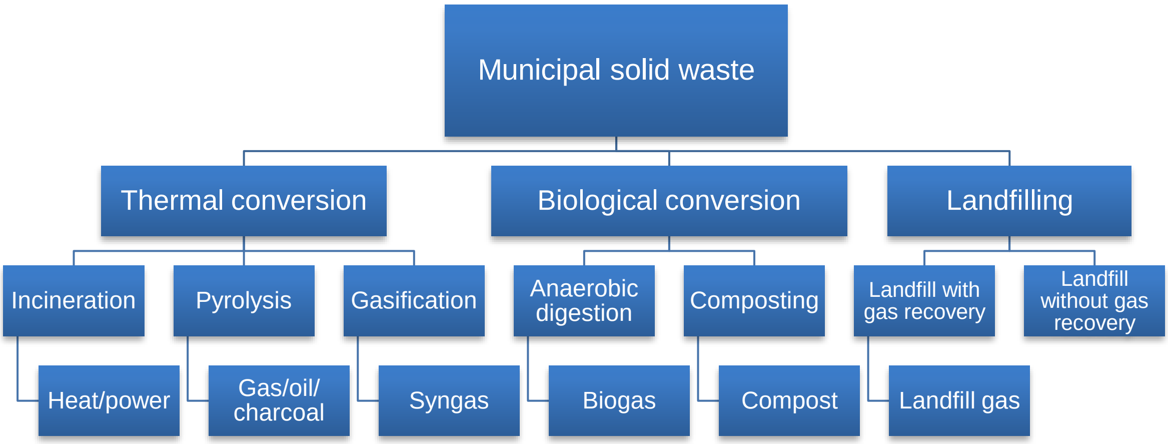

Figure 2-3: Technological options for waste-to-energy (adopted from Kumar & Samadder, 2017).

Table 2-1 specifically focuses on incineration, gasification, pyrolysis and anaerobic digestion as WtE technological options (alternatives to landfilling). The table provides the technology description, major products, waste inputs and volume reduction, pollution control requirements, approximate cost, scale of the plant, extent of use and general applicability of the different options.

Table 2-1: Different WtE technologies and considerations for their application (Kumar & Samadder, 2017; United Nations Environmental Program, 2019)

Type of Technology	Incineration with energy recovery	Gasification	Pyrolysis	Composting	Anaerobic Digestion
Technology description	Direct combustion of waste between 750 and 1100ºC in the presence of oxygen.	Partial oxidation of waste between 800 and 1200ºC in the presence of a controlled amount of oxygen.	Thermal degradation of waste between 300 and 1300ºC in the absence of oxygen.	Aerobic bioconversion of organic wastes.	Biodegradation of (readily degradable) organic wastes in the absence of oxygen, with anaerobic microorganisms.
Major products	Produces steam for electricity and/or heat generation in a boiler or steam turbine.	Produces synthetic gas for further combustion or conversion to chemical feedstock.	Produces liquid fuel for further combustion or conversion to chemical feedstock.	Produces compost which can serve as a soil conditioner, mitigate erosion, sequester carbon in soil, be used in land reclamation and as a final cover for landfills.	Produces biogas and digestate. Digestate can be composted for use as a soil conditioner or dewatered and used as a low CV RDF.
Waste input	Mixed MSW or refuse-derived fuel.	Only suitable for relatively homogeneous waste streams, such as wood waste, agricultural residues, sewage sludge, and plastic waste.		Separated organic fraction of MSW, food waste, or other solid organic waste. Suitable to treat material high in lignin.	Separated organic fraction of MSW, food waste, animal/human excreta, or liquids and sludges. Less suitable for high in lignin material.
Volume reduction	75 – 90%	75 – 90%	50 – 90%	95 – 100%	45 – 50%
Pollution control requirements	High	Medium	Medium	Low	Low-medium

Type of Technology	Incineration with energy recovery	Gasification	Pyrolysis	Composting	Anaerobic Digestion
Cost per tonne (in Rands)	R1750 – R3500 For centralised facilities on a moderately large scale.	R1750 – R3500 For centralised facilities on a moderately large scale.	R1750 – R3500 For centralised facilities on a moderately large scale.	R0 – R3050 For small-scale composting. At a pilot site running in Phnom Penh, Cambodia, for example, the cost can be made-up by the value of the end product.	R1200 – R2200 For centralised facilities on a moderately large scale. Cost depends on subsidies for renewable energy.
Scale of plant	Available from small to large scales. A centralised large-scale plant is more common.	Available from small to large scales.	Available from small to large scales.	Available at the household scale, community scale or at a centralised, large scale (window, aerated static pile, in-vessel).	Available in decentralised small-scale digesters (including on-farm), and large-scale digesters for the organic fraction of MSW.
Extent of use	Widely applied in Europe, Japan and the United States. Increasing application in developing countries.	Not widely applied and only available at small scales. Commercial gasification plants are established in Japan and the Republic of Korea.	Not widely established for MSW.	Widespread in high-income countries. Asia has a long tradition of making and using compost.	Widespread use for non-MSW and increasing use for clean organics from separate collections of MSW, including using anaerobic digestion followed by composting.
General applicability	Suitable for mixed MSW but the waste quality and composition may not be suitable without specific pre-treatment such as pre-drying.	Potential for wood gasification technology.	Not established yet in developed or developing countries.	High potential, particularly in developing countries with a high organic fraction of MSW. Not yet widespread due to operating costs and the need for source separation.	Small-scale anaerobic digesters are used to meet the heating and cooking needs of individual rural communities.

Reflecting on Table 2-1, WtE systems are complex and are not a “one-size-fits-all” process. This implies that the policy context applicable to a specific country will also inform the technological options, which may be considered in that specific country.

2.3.2 Waste-to-energy (WtE) policy context

The most critical factor in adopting RDF is having a policy framework that promotes the circular economy. Many countries like Spain, Mexico, and China have approved the co-incineration of RDF for different purposes (Khan *et al,* 2022). In Europe, the European Commission passed the *Landfill Directive* 1999/31/EC, which requires diversion from landfills of the biodegradable fraction of MSW and used tyres. A similar policy called the *Waste to Resource* policy was passed in South Australia. The framework implemented a standard for RDF production and use (EPA, 2010). In India, an expert committee was constituted by the Ministry of Housing and Urban Affairs (MoHUA) in 2017 to develop guidelines and relevant recommendations on the utilisation of RDF in various industries (Chavando *et al*., 2022). These countries either witnessed or increased Refuse Derived Fuel adoption following these policies.

The sub-sections below aim to provide an overview of the policy framework applicable to GHG emission mitigation and WtE. The intent of these sections is not to provide the entire policy and legislative context applicable to WtE but to focus on the policy environment applicable more specifically to the research scope, which focuses on the co-processing of municipal solid waste as an alternative energy source in cement production.

2.3.2.1 Environmental Justice and Sustainable Development Goals

Constitutionally, WtE has been supported by the theory of *Environmental Justice* (EJ), which began initially in the USA as early as the 1970s. Energy Justice was based on work by political philosophers in the radical justice tradition such as Fraser, Young and Honneth (Svarstad *et al* 2020). As a result of their work, a radical environmental justice framework within Energy Justice focuses on three core elements: distributive justice, recognition, and procedural justice in connection to the unequal distribution of environmental pollution. In waste management, environmental and energy justice was associated with unproperly managed waste treatment facilities (especially incineration facilities), and the environment including health issues Godfrey *et al*., 2019).

The trio policies of energy, waste and environmental management have changed the outlook on waste-to-energy adoption, where human health is included in the latter. In 2015, the United Nations launched the 2030 Agenda for Sustainable Development, which outlines 17 Sustainable

Development Goals (SDGs) (UN, 2015). The SDGs have been the foundation of extensive research, political support, and civil society engagement in climate change mitigation. Historically, The SDGs marked a milestone of long-term efforts to integrate environmental and socio-economic issues into the way we live.

By supporting the theory of energy democracy and responsible waste management, WtE could potentially meaningfully contribute to SDGs 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), 8 (Decent Work and Economic Growth), 9 (Industry Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production) and 13 (Climate Action).

2.3.2.2 Legal framework focusing on climate change and air quality management

International cooperation among countries to curb global warming can significantly lower greenhouse gas emissions. Looking back at the Kyoto protocol, which was a historic landmark, the first legally binding climate change framework, the world has engaged and researched further on effective ways to tackle global warming. The sub-sections below will explain the past and active policies aimed at reducing climate change and improving air quality management.

2.3.2.2.1 The Kyoto Protocol

The Kyoto Protocol was a predecessor of the United Nations Framework Convention on Climate Change, which came into effect in 1994. The protocol only came into effect in 2005, sharing the convention's objective to stabilise atmospheric greenhouse gas concentrations to enable a global response to climate change (Miyamoto, 2019). The Protocol sets binding targets for developed countries to limit or reduce greenhouse gas emissions. The Kyoto Protocol and clean development mechanisms have significantly affected the cement industry globally.

The applicability, effectiveness, and potential impact of these policy instruments on WtE and the global cement industry could support the replacement of fossil fuels with waste-derived fuels (Rehan and Nehdi, 2005).

The Kyoto Protocol introduced three international market-based instruments through which reduction in GHG emissions could be reached: clean development mechanism (CDM), joint implementation (JI), and emissions trading (ET). Allowing the trading of GHG emission permits globally, these instruments enabled countries to reduce emissions or enhance "carbon sinks" at lower costs. The protocol further established innovative mechanisms to assist these Parties in meeting their emissions commitments. In particular, the protocol laid down specific rules concerning the reporting of information by Annex I Parties have to demonstrate that they are meeting their commitments and review this information (Shishlov *et al.,* 2016). The protocol successfully reduced the emissions of trading countries by approximately 7% (Mamoun, 2019). However, the Kyoto Protocol was not inclusive of all developing countries, which significantly added to environmental pollution in these developing areas. The new developments called for a more inclusive system where member countries had access to funding through a national determined contribution. Following such needs, the Paris Agreement was established in 2014.

2.3.2.2.2 Paris Agreement

Compared to only 150 Kyoto Protocol members, 196 countries united to limit global warming to below 2 degrees, preferably 1.5 degrees Celsius (UNFCC, 2016) as part of the Paris Agreement. After the Kyoto Protocol revision in 2009, the Paris Agreement became binding legislation. The (NDC) National Determined Contribution policy significantly added to the Paris Agreement. The Paris Agreement gave the 193 members a five-year plan to reduce carbon footprints in their countries by financially subsidising climate change projects and passing climate change investment policies. Such changes increased the use of energy-efficient equipment, process modifications, fuel switching to waste as an alternative fuel, and cement blending using industrial by-products have helped decrease the carbon dioxide emissions associated with energy conversion (Bosoaga *et al.,* 2009 & Böhringer et al., 2021).

South Africa submitted its first NDC with the UNFCCC in October 2015, committing to keep national GHG emissions within a range from 398 to 614 Mt CO_2-eq for 2025 and 2030 (*Ross et al*, 2021). Regardless of the NDC contributions, in 2015, South Africa's GHG emissions were estimated at 460 Mt CO_2-eq, ranking as the 14th largest contributor to carbon dioxide emissions in the world. The NDC submission showed the need for immediate action in carbon reduction since the "peak, plateau and decline" approach will not immediately address climate change.

The NDC was not the only climate change initiative South Africa had taken. Since 2009, a few climate change conducive legal frameworks have aimed to promote the circular economy in the waste management context. The 2011 and 2020 National Waste Management Strategies highlight the importance of WtE projects as an alternative to landfilling, while the *National Policy on the Thermal Treatment of General and Hazardous Waste* (GN. 777 of July 2009) promotes energy recovery from waste, by specifically focusing on co-processing in high-temperature installations, such as cement manufacturing. Furthermore, the *Norms and Standards for the Assessment of Waste for Landfill Disposal* GNR. 635 of August 2013 (Molewa, 2015) (Hanto *et a.,l* 2022) prohibits the disposal of hazardous waste with a high calorific value, which could be used for energy recovery.

These developments came after many years of research supporting the waste hierarchy as an integrated waste management plan. Furthermore, the political commitment adopted in the Paris climate agreement, coupled with the rising waste disposal, encourages the search for new sources of energy that are more sustainable and compatible with environmental protection (Ang *et al.*, 2022).

2.3.2.2.3 National Climate Change Response Policy White Paper and Climate Change Bill of 2022

Following the White Paper on Climate Change in 2020 by the South African Government, with a vision for an effective climate change response between 2020-2025, the South African government gazetted the Climate Change Bill of 2022. The Bill calls for urgency and national response to curb greenhouse gas emissions by focusing on areas such as carbon pricing, water, agriculture, disaster management and biodiversity. Above all, the Climate Change Bill emphasises accountability in greenhouse gas reduction. The Ministers in high-emitting industries such as the Ministry of Energy, Transport and the Ministry of Environment are tasked to set up regulations that reduce and record the current sectoral emissions.

Following the carbon sectoral audit, the ministers are tasked to implement systems that allow carbon budgeting to facilitate an annual carbon inventory. These goals are achieved through tools such as incentivising and disincentivising processes that may affect reducing the carbon inventory. Any decision must consider the social benefit and consult the private sector to accommodate maximum benefit to all stakeholders.

The Bill calls for a municipal forum on climate change. Municipalities are instructed to analyse carbon-emitting activities within their districts by using the best available technology, science, evidence and information. Newer technologies suggested in the Climate Change Bill can be guided by the NEMAQA Act (National Environmental Management Air Quality Act of 2004.

2.3.2.2.4 The National Environmental Management Air Quality Act (NEMAQA) (39 of 2004) and List of activities which result in atmospheric emissions which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions, or cultural heritage (GNR 893 of 22 November 2013)

The National Environment Management: Air Quality Act 39 of 2004 intends to: *“reform the law regulating air quality in order to protect the environment by providing reasonable measures for the prevention of pollution and ecological degradation and for securing ecologically sustainable development while promoting justifiable economic and social development; to provide for national* *norms and standards regulating air quality monitoring, management and control by all spheres of government; and for specific air quality measures".*

In 2010, the Department of Environmental Affairs published a list comprising activities that result in atmospheric emissions which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions, or cultural heritage in terms of section 21(1) (b) of the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004) (GN 248, Gazette No. 33064, 31 March 2010). The list was amended under GN 893, Gazette No. 37054 of 22 November 2013 (Molewa,2015). These activities include (amongst others) solid biomass combustion installations (subcategory 1.3), waste co-feeding combustion installations (subcategory 1.6), cement production (using alternative fuels and/or resources) (subcategory 5.5) and thermal treatment of general and hazardous waste (subcategory 8.1), which may all relate to WtE technologies. These activities require an application for an atmospheric emissions licence to monitor, manage and mitigate resultant emissions. This act is evidence South Africa is not passive about the anthropogenic activities within the country. Especially given the nation is part of the G20 countries, heavily involved in the mining and usage of coal.

2.3.2.3 Legal framework aimed at transforming to a less carbon-dependent energy production

Coal is the most carbon-intensive fossil fuel and phasing it out is a pivotal step to achieving the emissions reductions needed to limit global warming to 1.5°C, as shown in the Paris Agreement. Furthermore, most emissions from coal are in the electricity and cement manufacturing sectors. as we already have the technologies that can replace coal, phasing out is a relatively cheap and easy option to reduce emissions. This section shows the local and global ongoing engagements, such as the G20 countries' coal phase-out programme and the South African Integrated Resource Plan.

2.3.2.3.1 The G20 Countries Coal Phase-Out Management

According to the Intergovernmental Panel on Climate Change's (IPCC's) Special Report on Global Warming of 1.5°C, a near-total reduction in the use of coal and other fossil fuels for electricity generation by 2050 is necessary if the temperature goal of the Paris Agreement is to be reached, with reductions of approximately two-thirds by 2030. The G20 countries are the most significant users and exporters of coal. Therefore, they must embark on a process of phasing out coal. About 30% of the primary energy supply of the G20 countries is derived from coal. In many G20 countries, coal is the largest contributor to greenhouse gas emissions. As outlined in Figure

2-4, of the G20 countries, South Africa (68%), China (64%), India (44%) and Australia (33%) have the highest coal share in domestic primary energy supply (Ernedata, 2018) (Figure 2-4).

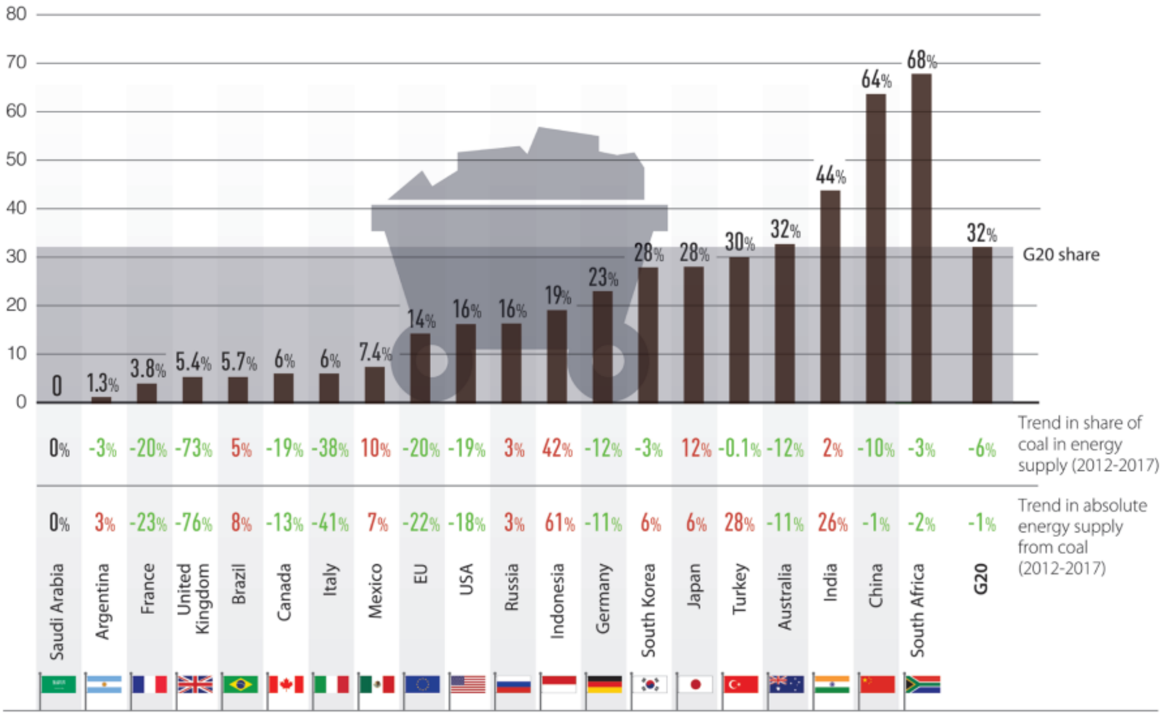

Figure 2-4: The G20 countries coal use trends (Ernedata, 2018)

South Africa has 42 gigawatts (GW) installed coal capacity and a further 14 GW under construction. This is the largest share of coal in both energy supply and electricity generation (89%) in the G20 group, although with a slightly decreasing trend (-6%, during 2012–2017) 5th biggest coal exporter in the G20 (5% of global coal exports). Often, a coal phase-out requires broad political and societal support. South Africa relies heavily on coal power. The 2019 updated draft Integrated Resource Plan (IRP) for electricity envisages the completion of major plants and the construction of new coal power plants in the 2020s but also assumes that the share of coal will be reduced. Besides reducing pollution, the continued use of coal brings out a risk of standard assets in investments in coal-fired plants due to the shifting in economic trends and policy on renewable energy (Hollins *et al.,* 2017). The South African government set the integrated resource plan to manage sustainability in energy investments to stay ahead of such change.

2.3.2.3.2 South Africa Integrated Resource Plan (IRP)

The IRP is an electricity infrastructure development plan based on the least-cost electricity supply and demand balance, considering the security of supply and the environment (minimising negative emissions and water usage). The energy sector contributes close to 80% towards total emissions, of which 50% are from electricity generation and liquid fuel production. The country's vast coal deposits cannot be sterilised due to the unavailability of technological innovations that could be deployed to use this resource in an environmentally sensitive manner. The IRP is an initiative to pursue a diversified energy mix that reduces reliance on a single or a few primary energy sources. The extent of decommissioning of the existing coal fleet due to the end of design life and commitment to reduced emissions post-2030 could provide space for a completely different energy mix relative to the current mix. The IRP is consolidated with the Renewable Independent Power Producer Programme (REIPPP), aimed at bringing additional megawatts onto the country's electricity system through private sector investment in wind, biomass and small hydro, among others. Biomass technologies are mainly dominated by waste-to-energy, and they are a trio of policy solutions given that they supply energy, reduce greenhouse gas emissions, and reduce landfilling of waste (Malinauskaite and Jouhara, 2019).

2.3.2.4 Legal framework aimed at reducing the disposal of waste in landfills

The next sections provide an overview of the legal framework applicable to the reduction of waste disposal to landfill sites.

2.3.2.4.1 Waste management hierarchy

In 1975, The European Union's Waste Framework Directive (1975/442/EEC) introduced the elements of the waste hierarchy concept into European waste policy for the first time. In 2008, the European Union introduced a five-step waste hierarchy to its waste legislation, Directive 2008/98/EC, which set the path for the circular economy as we know it. The waste hierarchy developed a four-tiered waste management hierarchy to guide waste management decision-making. The waste hierarchy was globally adopted from Europe to the Environmental Protection Agency, the USA (EPA) and Africa (see Figure 2-5). South Africa legislated the waste management hierarchy as it is entrenched in Section 17 of the NEMWA. The Act has since been a base line of the Integrated Waste Management Plans of South African Municipalities, transforming how municipalities manage waste.

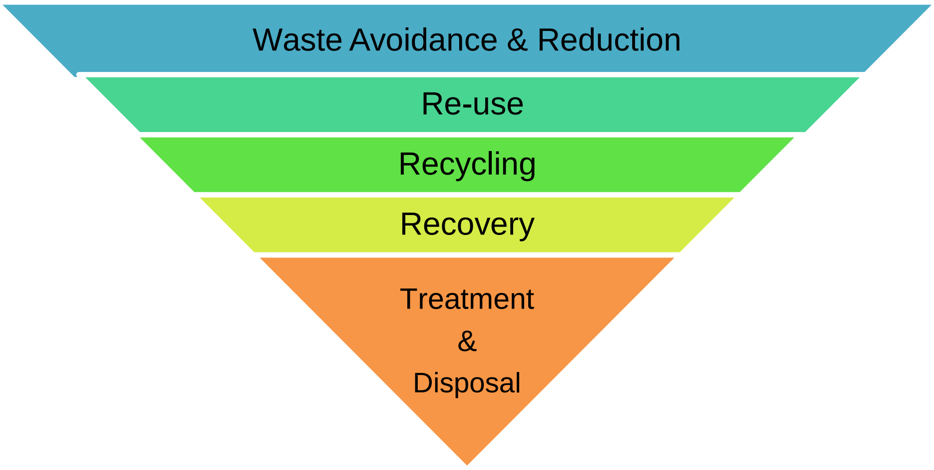

Figure 2-5: The waste management hierarchy (adapted from DEA, 2011).

As shown in Figure 2-5, waste avoidance is the advised and prioritised method. If waste cannot be avoided, it can be prepared for reuse. If waste cannot be re-used, it may be recycled. Recycling and recovery are complementary waste management methods. Waste recovery involves thermal treatment, which is needed for residual waste unsuitable for recycling. Improving municipal solid waste management through technical innovations such as thermal treatment technologies like waste drying, pyrolysis, gasification, compost and digestion of organic waste, and landfill mining could improve the urban carbon cycle by reducing carbon emissions (Rogoff & Screve, 2019). As depicted by the waste-to-energy (WtE) hierarchy (Figure 2-6), WtE technologies can be assessed in the context of the waste hierarchy.

However, it is important to note that the waste hierarchy is not a ladder for a waste management system. Developing countries should consider leapfrogging and adopting a top-down approach to introduce the 3Rs in their waste management systems before considering thermal. The South African constant review of the National Waste Management Strategy 2008 & 2020 exemplifies how the country is progressing in implementing the circular economy. Furthermore, programmes such as the integrated Resource Plan (2020) focus on moving from carbon (coal) based energy sources to sustainable alternatives contributing to climate change mitigation.

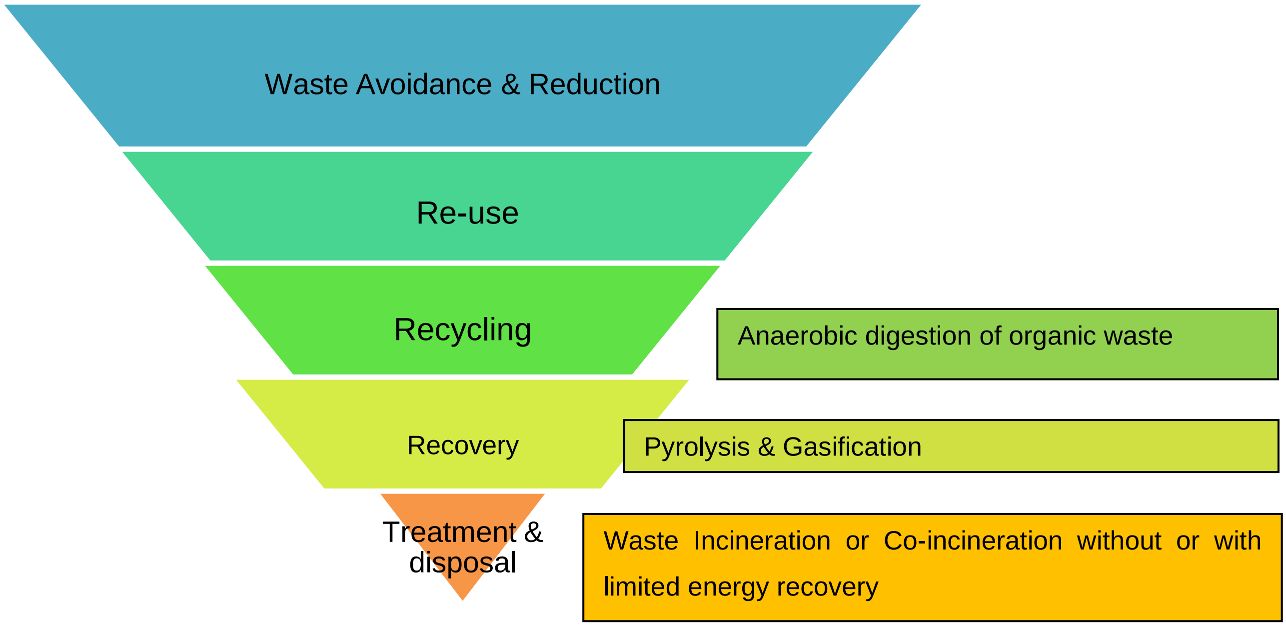

Figure 2-6: Waste-to-energy (WtE) hierarchy adapted from European Commission, 2017a (Hollins *et al.,* 2017)

Like the waste management hierarchy, the main priority will always be waste prevention, followed by reuse and waste recycling, which is a broad aspect. Recycling waste-to-energy is constituted by aerobic and anaerobic digestion. In South Africa, digestors are becoming a prominent practice where the only existing solid waste-to-energy plants is an anaerobic digestor (Kang *et al*, 2019). Compared with anaerobic digestors, aerobic digestion can convert MSW into electricity, CO_2 but cannot significantly reduce solid waste problems as methane is a notorious greenhouse gas (Refer to Table 2-1). This is because methane (CH_4) has a much higher potential as a GHG than CO_2, and the global warming potential from CH_4 is 21 times higher than from CO_2. For example, diverting one tonne of waste from a landfill towards anaerobic digestion to produce biogas and fertilisers can prevent up to two tonnes of CO_2 equivalent emissions (Bernstad and Jansen, 2012).

Further, pyrolysis can be allocated to the ‘recovery’ category on the list of GHG-limiting technologies. Conventional pyrolysis decomposes materials at elevated temperatures by relying on direct heating techniques, such as electric heaters, with naked flames or exposure to hot media (Jouhara *et al*., 2017a). Table 2-1 above reveals a fair comparison of the available waste-to-energy systems around the world. Pyrolysis significantly recycles waste and does not require much pollution control. In comparison, gasification recycles the most solid waste sustainably. Gasification seems to be the ideal waste-to-energy thermal treatment heat source. Gasifiers have a higher cost per tonne as waste-to-energy sources, but they are similar to incinerators which are close comparisons. However, waste incineration can be classified as disposal as it burns all MSW for heat recovery. Incinerators require high pollution control mechanisms and accommodate a form of solid waste. To integrate such industrial developments with the law regulating waste management in South Africa to protect health and the environment by providing reasonable measures for the prevention of pollution and ecological degradation and for securing ecologically sustainable development.

2.3.2.4.2 National Environmental Management Waste Act (59 of 2008)

The National Environmental Management Waste Act (59 of 2008) (NEMWA) provides a holistic approach to addressing inefficiencies hindering the success of sustainable waste management (Papenfus *et al.,*2015). To protect public health and environmental standards, the South African Ministry of Environment reformed the law regulating waste management to provide reasonable measures for preventing pollution and ecological degradation. For instance, Chapter 16 of the Act provides the general duty with respect to Waste Management, while Section 17 provides for the waste management hierarchy. Section 16 of NEMWA corroborates the waste management hierarchy by urging the general public and industries to prioritise waste avoidance. Where waste cannot be avoided, waste can either be reused or recycled. The chapter was designed to improve and educate the country to manage waste in a considerate manner. All waste management should be environmentally friendly and considerate to the population of others by avoiding environmental pollution or noise pollution. Where any potentially hazardous waste activity is being done, the act requires the generator to inform the community in compliance with the norms and standards of that specific waste stream. These standards apply to all provinces of South Africa.

2.3.2.4.3 National Waste Management Strategy

The National Waste Management Strategy (2011, 2020) provides a platform to provide sustainable waste management in South Africa (Kenneth *et al*., 2022). The strategy is an effort in the form of a framework and strategic interventions for the waste sector to align with the Sustainable Development Goals (SDGs) of Agenda 2030 adopted by all United Nations (UN) member states who adapted these goals in 2015. Unlike the 2011 version, the 2020 version focuses on a “circular economy” aiming to reduce environmental impacts by re-use & recycling of processed materials. The reasoning to have materials that would end up as waste disposed of, or reprocessed rather than extracting raw materials again, is at the core of the concept of sustainable development. The idea and strategy are further expanded through the three strategic pillars of waste minimisation, effective and sustainable waste management, and enforcing waste compliance awareness. The strategy continues with critical interventions towards institutional arrangements, norms and standards, specific measures for problem areas, licensing, remediation, the national waste information system, compliance, enforcement, and stakeholder engagement (Creecy, 2020). In a nutshell, the strategy speaks to waste beneficiation, which is a circular economy practise that is compatible with the thermal treatment of waste in cement production.

2.3.2.4.4 National Policy on the Thermal Treatment of Waste (GNR.777 of 2009)

GNR.777 is a policy that presents the government's position on thermal waste treatment as an acceptable waste management option in South Africa. The policy is a response to the calls by the private sector and non-governmental organisations to permit thermal treatment of waste in the country, specifically in the co-processing of cement. In 2009, the DEA finally acknowledged the presence and capacity of cement kilns in South Africa to effectively process general and hazardous waste as alternative fuels and raw materials (AFR). Furthermore, the policy provides the framework for waste thermal treatment technologies such as incinerators, pyrolysis, gasification, and alternative fuel use in cement co-processing. The vision behind this policy is to promote sound waste management based on the waste hierarchy.

The policy further attempts to promote a public-private partnership in waste management by permitting cement kilns as waste treatment facilities. This is because the country has a network of cement production plants, presenting an opportunity for effective waste treatment and energy recovery. In this case, the GNR.777 not only supports energy recovery/ waste-to-energy from waste but also encourages diverting recoverable waste from landfill dumping.

2.4 Benefits of waste-to-energy (WtE) in South Africa

The following sub-sections will focus on waste-to-energy (WtE) implementation in South Africa. The sections focus on the economic-, environmental- and social benefits of WtE.

2.4.1 Economic benefits

The State of Waste Report (2018) indicates that South Africa disposes of approximately 98 million tonnes of waste through landfill per year. Of this disposed waste, approximately 56 million tonnes constituted reusable, recyclable, or recoverable solid waste (Nandy *et al*, 2022). In financial terms, such losses amount to at least R15 billion in potential value losses being continuously dumped annually (CSIR, Council for Scientific and Industrial Research, 2018; Stubbs, 2021). However, a different perspective on waste value interpretation suggests that the South African waste stream is not much recoverable through waste-to-energy.

According to the World Bank, organic waste makes up about 53% to 56% of municipal solid waste in low- and medium-income countries (Kaza *et al.*, 2018). This composition is ideal for energy recovery through anaerobic digestion, for instance, but may not be ideal for energy recovery during cement manufacturing. Contrary to this, the State of Waste Report (2017) reported that South Africa generates only 16% of organic waste, and 35 % constitutes paper mills, biomass, paper and pulp industry. This notion suggests that South Africa's municipal solid waste quality is likely low from an energy recovery (from refuse-derived fuel or RDF) potential perspective. Energy recovery from waste as RDF (i.e. for cement manufacturing purposes) requires waste with a relatively high calorific value, while the relatively high moisture content in the waste fails to meet the intensity of the flames as are necessary for energy combustion (Cheruiyot *et al.,* 2019). This may require some sorting, shredding and drying of MSW before it is suitable for use as RDF.

South Africa currently has only one Waste to energy plant in the Western Cape province (Chivandire, 2021). Other energy recovery infrastructure largely includes smaller biodigesters and energy recovery through co-processing of waste (mainly focusing on end-of-life waste tyres). There is also some MSW being exported to neighbouring countries, such as Namibia, for energy recovery purposes. Chivandire, (2021) argues that South Africa has not yet fully reached its energy recovery from waste potential. It remains to be investigated why energy recovery is not extensively exercised in South Africa, given that the policy framework supports energy recovery.

2.4.2 Environmental benefits

The physical mechanisms describing the link between changes in atmospheric CO_2 concentration and global temperature were first described more than a century ago. The potential effects of human activities on the carbon cycle, and the implications for climate change, were first noticed and studied by the Swedish chemist Svante Arrhenius in 1896 (Anderson *et al*, 2016). He realised that CO_2 in the atmosphere was a critical greenhouse gas and a by-product of burning fossil fuels (coal, gas, oil). He even calculated that doubling CO_2 in the atmosphere would lead to a temperature rise of 4-5 (Lindsey *et al*, 2014). After significant research by climate change pioneers such as R. Revelle and C.D Keeling in the 1950s in Mauna Loa, Hawaii, more awareness of the carbon cycle was conclusively communicated to the world's contribution to climate action.

The sections below discuss the potential environmental benefits of energy recovery from waste in more detail.

2.4.2.1 Reducing impacts related to the disposal of waste to landfill

Energy recovery from waste that would have been landfilled can lead to several environmental benefits. First, extracting energy from waste materials reduces the need to generate electricity from other sources that emit greenhouse gases into the atmosphere, such as burning fossil fuels.

By increasing the use of renewable energy, the production of these harmful emissions can be decreased, leading to cleaner air quality. Additionally, the energy generated can be used to replace non-renewable sources of energy, helping to reduce the amount of energy consumed overall and improve energy efficiency. Finally, energy recovery from waste can decrease the amount of material that is landfilled, reducing the overall volume of waste that needs to be stored, reducing air pollution, and preserving green spaces and resources (Nahman, 2011).

The prevailing rates of landfilling waste create a bias in the real cost to the environment. Nahman (2011), in his research on the negative externalities of landfilling in the City of Cape Town, argued the detrimental effects of the landfilling of waste are not always concrete (and economic) but are reflected in the cost of health and environment.

On the other hand, alternatives to landfill disposal, such as Wets, reduce the need to invest in the construction and maintenance of landfill sites. Landfill sites take up a lot of space (which could be used for other land uses), negatively impact habitats and landscapes, and cause the release of methane. Methane is more harmful to the environment than carbon dioxide because it is a much more powerful greenhouse gas. The comparative impact of methane on climate change is more than 25 times greater than carbon dioxide over 100 years (Houghton, 2003).

Modern economies have adopted contemporary solid waste management systems, including waste collections and segregation followed by one or more of the following options: recovery of secondary materials by recycling of solid wastes, biological treatment of organic waste, production of marketable composts, and thermal treatments by various forms of thermochemical conversions to recover energy in the form of heat and electricity and landfilling (Durak, 2023). The implementation of such systems reduces the environmental impacts that waste would otherwise have had on the environment, such as contamination of groundwater, soil contamination, air pollution (from transportation and disposal of waste), unpleasant odours and health impacts, and climate change impacts.

2.4.2.2 Reducing climate change impacts

Between 2000 and 2006, the world emitted roughly 234 billion tonnes of CO_2 and nearly one-third of the total trillion metric tonne “budget” was already spent. The section below addresses the implications of anthropogenic activities such as waste management and cement production on the carbon cycle.

2.4.2.2.1 The carbon cycle

Understanding carbon is the first step to optimising its benefit to the atmosphere. Carbon is the foundation of all life on earth, required to form complex molecules like proteins and DNA (Green *et al.* 2004). This element is also found in our atmospheric carbon dioxide (CO_2). As a result, carbon helps regulate the earth’s temperature, makes all life possible, is a crucial ingredient in the food that sustains us, and provides a significant energy source to fuel our global economy. Houghton (2003) and Riebeck (2011) describe the carbon cycle as the exchanges of carbon within and between four major reservoirs: the atmosphere, the oceans, land, and fossil fuels.

Land use activities such as waste management and coal use for energy have manipulated the carbon cycle (Keller, 2018). This is possible because, carbon may be transferred from one reservoir to another e.g., the emission of carbon from cement production into the atmosphere and the slow release of methane from landfill sites. These anthropogenic activities have compromised the natural carbon reservoirs.

2.4.2.2.2 The role of waste management in the carbon cycle

Solid waste management is one of the key variables in the ecosystem of urban metabolism, which significantly impacts urban carbon cycles. Zhou *et al.* (2015) explored the theory of urban metabolism by analysing the contribution of urban waste management to the carbon cycle. The carbon cycling of municipal solid waste was analysed, and the results indicated that the horizontal input flux in municipal solid waste has significantly changed over the years. Landfilling formed the most extensive carbon stocks, while incineration showed the most significant vertical carbon dioxide changes. Source separation and integrated technologies decreased carbon emissions by adding new carbon sources to the urban system (Zhong *et al.,* 2018). The waste-to-energy concept, therefore, significantly reduces the negative carbon impact of landfill disposal.

2.4.3 Social benefits

Landfill sites are associated with odours, harmful leachate, bacteria, particulate matter and fires that may present adverse social impacts on the surrounding communities (Caillat *et al.,* 2013). When waste is diverted from landfill sites, these impacts may be reduced.

Diversion of waste from landfill sites may also contribute to livelihoods and create job opportunities. Furthermore, waste-to-energy projects often involve community engagement programmes to promote awareness and education about waste management, recycling, and energy conservation. These initiatives help communities become active participants in waste reduction efforts and encourage sustainable behaviours.

Waste-to-energy processes generate electricity and heat by utilising the energy content of waste materials. This contributes to the diversification of energy sources and helps meet the increasing demand for electricity and heat in communities. It reduces reliance on fossil fuels, promoting a transition to cleaner and more sustainable energy production (Bras et al.2020).

Overall, waste-to-energy technologies offer multiple social benefits by promoting sustainable waste management, reducing environmental pollution, creating jobs, and supporting the transition to cleaner energy sources.

2.5 Energy recovery from refuse-derived fuels (RDF)

The sub-sections below specifically focus on the recovery of energy from refuse-derived fuels (RDF). It starts by defining the concept of RDF and then focuses on municipal solid waste (MSW) as RDF. The rest of the literature review continues to focus on the use of RDF and specifically aims to shed light on the use of RDF in cement production.

2.5.1 Defining refuse-derived fuels (RDF)

Refuse-derived fuels (RDF) are a form of alternative fuels (AF). AF is defined as combustible non-fossil solid fuel, waste, and by-products with a significant calorific value (Grammelis *et al*., 2021). AF is derived from the need to replace fossil fuels for environmental and economic benefits. AF is widely known and can be referred to with different terminologies, such as *secondary fuels* (SF) and *solid recovered fuels* (SRF). SRF is like RDF but with a much more closely defined and controlled specification (Breeze, 2018).

The physical and chemical properties of RDF are guided by ASTM European standards and various ISO standards. One of the popular standards is CEN/TC 343, which defines the grading of refuse-derived fuels (RDF), tyre-derived fuel (TDF), tyre-derived aggregate (TDA), and heavy fuel oil (HFO) (Lacovidou *et al.,* 2018). According to the EPA, RDF *is "durable goods, containers and packaging, food wastes, yard wastes, and miscellaneous inorganic wastes from residential, commercial, institutional, and industrial sources".* This definition excludes industrial waste, agricultural waste, sewage sludge, and all categories of hazardous wastes, including batteries and medical wastes.

2.5.2 Municipal Solid Waste (MSW) as RDF

Gendebien *et al*. (2003), Kara *et al*. (2011), Haas and Webber (2010) and Lowitt (2020) highlight that municipal solid waste (MSW) could be used as an alternative energy source and processed to become a refuse-derived fuel (RDF). This is because of the composition of combustible substances such as paper, plastic, fabric, and other waste streams present in MSW.

Sagala *et al.* (2018), as well as Genon and Brizio (2008), denoted that MSW consists of five natural combustible components and contains the following mass composition: 69% biodegradable waste, 14.5% nylon plastic bags, 1.5% textile, 4% paper, and 0.9% PET bottles. A combination of these combustible waste streams is modelled to make a homogenous fuel that can be a substitute for coal. Due to its availability and lower environmental impact than fossil energy resources, MSW is increasingly used in the chemical and power industries to substitute fossil fuels around the world (Khan *et al*., 2021).

2.5.3 The origins of RDF usage

Fossil fuels are mostly used as fuel for industrial processes due to their availability and affordability (especially in the early 1900s). However, due to increasing costs and concerns over climate change, the industry has been looking at alternative fuel sources, which may be able to replace fossil fuels partially or totally (Alter, 1987). Typical alternatives for coal as a fuel source include natural gas, alternative energy sources (solar, wind, nuclear or hydropower), fuel cells, biomass combustion, and more recently RDF.

The traceable early use of RDF is believed to have started in England and New York in the late 1890s, where combustible materials were separated for waste-to-energy purposes. Schwarzböck *et al*. (2018) report that RDF was used in Germany in the 1950s, where tyre-derived fuels were used as an alternative fuel in cement kilns. In 1973, Dr Jerome Collins formally introduced the concept of RDF, which included rejected solid parts of the MSW prepared from materials recovery facilities and contains a high calorific value (Tahir *et al.,* 2023). The USA and European countries have been quite progressive in using RDF for co-processing. Figure 2-7 shows progress in the co-processing of RDF in cement kilns across Europe, indicating the percentage of RDF used for energy recovery purposes in these countries' energy mixes.

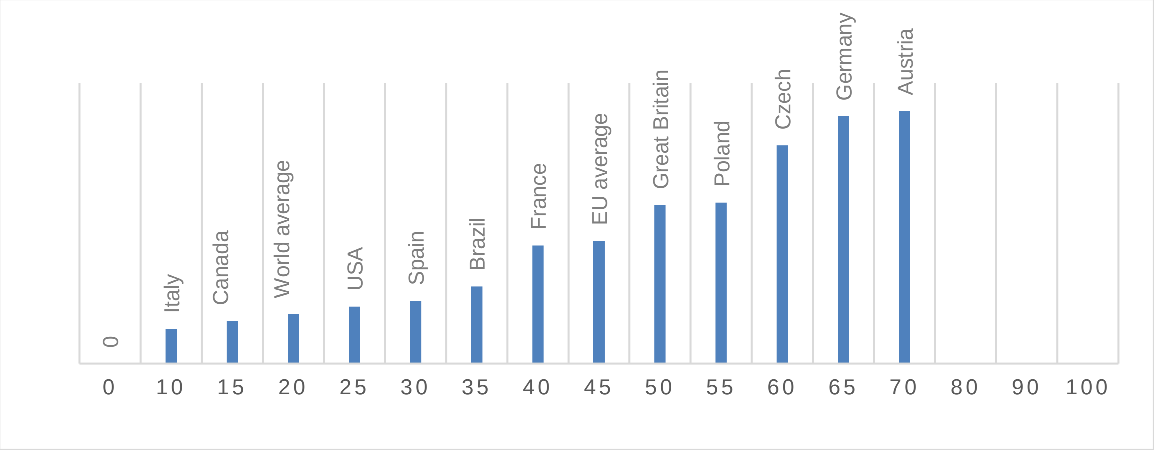

Figure 2-7: Percentage of RDF used by each country as part of their energy mix.

2.5.4 RDF to energy process

Most WtE facilities do not burn unsorted MSW due to the heterogeneous nature of the waste and moisture content, which could pose product quality and environmental concerns (Kara *et al*. 2011). The sub-sections below discuss the preparation of MSW for WtE purposes. The process should ideally start with the separation of waste at source, to optimise the volumes and quality of waste. This is normally followed by sorting, mechanical processing, drying, classification and storage.

2.5.4.1 Separation of waste at source

MSW is more difficult to handle than industrial wastes typically generated from mono-streams because it is not homogeneous. Mixed, unsorted MSW are unsuitable for energy recovery (Okedu *et al*., 2022). Source separation of organic waste from mixed MSW ensures the possibility of preparation of quality fuel for cement production (lower moisture content, higher heating value, lower ash content compared to unsorted MSW) (Arina *et al*., 2021).

The best method of waste segregation is separation at the source, which is considered an essential component in the appropriate treatment of MSW (Zhuang *et al*., 2008). Separation at source involves separating waste at the point of generation into different waste streams (i.e. paper, plastic, glass, organic waste, etc.). When recyclables and non-combustible MSW are separated before waste collection, the waste quality is optimised from processes such as pyrolysis and composting (Kungkajit *et al* 2015).

Waste separation at the source has been carried out in developed countries such as Japan, Germany, and Sweden for a long time and is currently in a relatively mature stage (Bundhoo, 2018). Economic incentives and a supporting legal context are essential to promoting residents' waste separation at the source practices (Alhassan *et al*., 2020). In Austria, and Vienna, waste drop-off centres are in place for the delivery of bulky, electrical, and hazardous waste. In addition, green waste drop-offs incentivised the community with high-quality aerobic compost of biowaste/greens (only garden refuse and not kitchen waste). Such an incentive provides a practical working system and promotes active community participation.

Waste separation at source is still in its infancy in South Africa (Moodley, 2014). Roos *et al.* (2019) conducted a case study in Abaqulusi Local Municipality in KwaZulu-Natal, South Africa, where only 16% of households were reported to be participating in waste separation practices. This supports Moodley's claim that South Africa's communities are not yet knowledgeable enough to be reliably integrated into waste management practices such as separation at source. In South Africa, informal waste pickers have, however, been contributing to the recovery or recyclable or recoverable waste separation/reclamation from the MSW waste stream (Schenck & Blaauw, 2011; Velis, 2017)

Waste pickers are active in many developing countries, including Serbia, Brazil, Tunisia, and the Philippines. Recently, policies have focused on waste picker integration as a critical component of official recycling systems (Scheinberg *et al.*, 2018; (Fei *et al*., 2016); (Samson, 2020). In addition, the World Bank endorses waste picker integration for various socio-economic reasons (Faltas, 2019). According to Maleka & De Wet (2020), South Africa has more than 60,000 waste pickers who substantially contribute to the waste management industry of the country, collecting 80 to 90% of recyclables per year. The South African Waste Pickers (SAWPA) supports the waste pickers. SAWPA members reclaim materials such as organics, plastic, cardboard, paper and metals, preventing them from going to waste dumps (Marnce, 2022). In the second National Waste Management Strategy (Creecy, 2020), the government committed to guiding municipalities and industry on measures to improve the working conditions of waste-pickers. Since then, the policy approach has evolved to formally recognise waste pickers as employees (Samson *et al.,* 2020). The increase in waste picker participation certainly improves the economic benefit of the integrated waste management plan. It directly contributes to energy recovery by pre-sorting plastic waste such as Polyvinyl chloride, which can have too much unfavourable chemicals for the combustion of refuse-derived fuels, but however highly recyclable

When separation at the source is not available, waste is usually sorted at the processing site through a material recovery facility (MRF).

2.5.4.2 Waste sorting

Further waste sorting may be required to separate wastes suitable for use as RDF (i.e. paper and plastic) from unsuitable waste streams (i.e. organic waste, glass, electronic waste, etc.). This sorting may occur at either a clean or a dirty material recovery facility (MRF). A dirty material recovery facility involves segregating valuable feedstock/ waste from a mixed 'dirty' waste stream rather than separating the components of a segregated 'clean' waste stream (Bourtsalas & Themelis, 2022). Sorting methods include manual sorting, magnetic sorting, electrostatic stacking, pneumatic sorting and photo-electric sorting (Edo *et al*., 2016).

MRFs are critical in the separation of iron and steel impurities from plastics. Some MRFs use electrostatic sorting, which uses plastics with different charging characteristics under electrostatic induction. While other MRFs use pneumatic sorting, which uses various plastics with varying resistances in the air. Sorting through a MRF can also be separated by photo-electric sorting according to plastic material. While different types of wastepaper have different fibre types, components, and properties, sorting wastepaper can achieve the purpose of grading and making the best use of it. Inert materials such as sand, glass and metals are eliminated from incoming MSW through manual or mechanical sorting (Sakri *et al.*, 2021).

2.5.4.3 Processing of RDF

RDF are produced from a systematic process of MSW separation, crushing, drying, classifying, secondary crushing, and in some instances, pelletising (see Figure 2-8) (Suryawana *et al*., 2021;

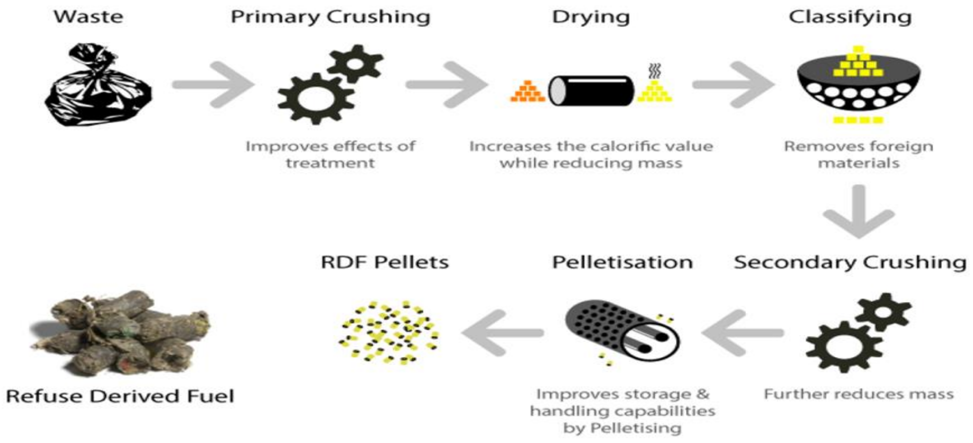

Figure 2-8: RDF cycle (CD Waste UK, 2022)

2.5.4.3.1 Primary crushing or shredding

After sorting, waste is subjected to primary crushing or shredding. The relevance of shredding comes from the need for a homogenous and compact fuel (Chen *et al*., 2020). The shredded waste is typically homogenous and contains high moisture levels, which require drying. Due to MSW heterogeneity, different methods are used to make RDF's physical characteristics homogenous. Table 2-2 shows different approaches to fragmenting MSW into a uniform product.

Table 2-2: RDF homogenising process

Steps	**Kara *et al.* (2011)**	**Arina *et al.* (2020)**	**Wotjecha *et al*. (2021)**	**Hemidat *et al.* (2019)**
Step 1	Shred to 200mm	Manual sorting	Sorting- bag opener	Waste sorting
Step 2	Fe separator	Shredding (< 300)	Drum separation (<60 mm)	Pre-shredder
Step 3	Ballistic separator to (80 mm)	Drum separator	Magnetic/manual separation	Magnetic separation
Step 4	Shredder (30 mm)	Electromagnetic/current separator (20 mm)	Cutting mill (30 mm)	Secondary shredding
Step 5	Drying	Mechanical biological treatment	Biological treatment	Mechanical Biological Treatment
Step 6	Baling	Shredding	RDF Baling	RDF packaging

2.5.4.3.2 Drying

MSW has great potential for energy production, especially in a developing country such as South Africa. To accommodate MSW in energy recovery, drying is necessary. The concept of drying has evolved from biological to mechanical and recently to thermal drying technologies. To make MSW combustible, it is essential to improve RDF heating value. Drying of MSW involves mass and heat transfer which is affected by external variables such as humidity, temperature, and air velocity as well as internal variables, e.g., material surface, physical structure, chemical composition, size, and shape (Ngamket *et al.,* 2021). Different types of technologies are used in dry MSW as outlined in Table 2-2.

In most cases, mechanical/biological treatment (MBT) is generally used for drying in several waste management processes such as material recovery facilities (MRF), RDF production, mechanical separation, sorting, composting and pasteurising. According to Hemidat *et al.* (2019), MBT is the ideal MSW treatment process to produce RDF. Depending on the end user's requirements, MBT can be customised to get the desired RDF quality. As the name suggests, MBT involves two types of processing: mechanical processing, sorting, separation, size reduction, sieving, and biological processing. It can be aerobic, anaerobic, or another biological process that converts biodegradable waste into stabilised waste organics components. The fuel contents mainly consist of plastics, paper and textiles and are processed into an RDF creating a product with high calorific value (Cheela *et al.,* 2021).

After sorting, shredding, and drying, RDF can either be used as loose material (fluff) or pelletised. Pelletising is known to up the calorific value and bulk density. Ziaee *et al.* (2016), in their case study of the Lowshan cement factory, determined that the best choice of RDF was fluff. Their results represent that using RDF (fluff) as an alternative fuel could raise the heating value and lower production costs.

2.5.4.3.3 Classification of RDF

RDF is classified by measuring physical properties (metals analysis, density, moisture) and chemicals (CV, ash content, sulphur, and chlorine content) (Hemidat *et al.*, 2019). As mentioned earlier, due to the heterogeneity of solid waste, the need to standardise RDF becomes gradually necessary for some quality control and consistency. The application of certification and quality management standards in thermal waste treatment, along with the use of new terminology, may enhance public acceptance and consistency in the thermal utilisation of this resource in industrial facilities (Vounatsos. *et al.,* 2015). However, RDF does not have a universal measurement standard for all physical and chemical properties. Each component can be tested with a different test method, depending on the available resources of the researcher. For instance, in Latvia, Arina *et al.* (2020) measured chemical properties using EN standards, where their moisture analysis utilised the EN 15414-3:2011 standard. For the same test, Hemidat *et al.* (2019), in their research in Egypt, used a net weight method of measuring the percentage change in mass before and after heating the samples. Regardless of the differences in test methods, results can be achieved and traced due to the integrity standards.

The classification of RDF differs in different regions, but the European standards (DIN EN 51900-1, 51900-2 and ASTM) seem globally acceptable for RDF grading (Genon & Brizio, 2008).

Table 2-3: **ASTM Classification of RDF (Source ASTM Classification 2008)**

Class	**Form**	**Description**
RDF-1 (MSW)	Raw	MSW with minimal processing to remove oversized bulky waste
RDF-2 (C-RDF)	Coarse	MSW is processed to coarse particle size with or without ferrous metal separation such that 95% by weight passes through a 152 mm square mesh screen
RDF-3 (f-RDF)	Fluff	Shredded fuel derived from MSW is processed for the removal of metal, glass and other entrained inorganics. The particle size of this material is such that 95% by weight passes through a 50 mm square mesh screen.
RDF-4 (p-RDF)	Powder	Combustible waste fraction processed into powdered form such that 95% by weight passes through a 10-mesh screen (0.89 square mm)
RDF-5 (d-RDF)	Densified	Combustible waste fraction densified (compressed) into pellets, slugs, cubettes, briquettes or similar forms
RDF-6	Liquid	Combustible waste fraction processed into a liquid fuel
RDF-7	Gas	Combustible waste fraction processed into gaseous fuel

As per the ASTM standards, the classification or grading of RDF is divided into seven groups (Table 2-3), with each of these fuels having different properties as indicated in the table.

Analysing such properties of RDF is relevant because they can influence the ignition, combustion behaviour, slag formation, corrosion potential, and energy conversion efficiency of RDF. However, the classification of refuse-derived fuels has been met with different conclusions, especially on which main parameters affect the quality of RDF (Bessi *et al*.2016).

RDF can take a variety of forms which have been proposed for use in several types of boiler units. NCRR (1980) researched that RDF can be either be:

- Shredded/air classified RDF, also known as fluff;
- Proprietary RDF / pulverised; or
- Pelletised RDF or densified (d-RDF).

Most RDF processes, however, implement either fluff or pellets. Kaddatz *et al*. (2013) researched that pelletising has the advantage of being hydrophobic through implementing hydrolysis, a continuous-flow autoclave that runs at a higher temperature and pressure than an autoclave (Hajinezhad *et al*, 2016). Pelletised fuel has more density; thus, a higher calorific value is achieved. To successfully pelletise RDF, a strict combination of variables must be maintained. Even though fluff RDF has consistency in its energy value, it often has a faster combustion reaction that results in higher incomplete combustion than pelletised RDF (Rezaei *et al.*,2020).

Fluff RDF is less dense; hence the oxygen rate depletes faster, resulting in higher flue gases and carbon monoxide levels than pelletised RDF.

2.5.4.3.4 RDF storage

RDF facilities must have provisions for storing raw waste and prepared fuel. Roughly two or three days of raw waste storage and four days of RDF storage are usually provided to cater to fluctuations in delivery volumes (Grillo, 2013). RDF facilities generally use a tipping floor instead of a pit to store unprocessed and processed waste. Raw waste and RDF are stored in separate buildings and pushed into piles using front-end loaders. The loaders also recover the waste, feed it to the processing lines, and feed the RDF to the boiler feed lines. The RDF is loaded as bales by a forklift truck onto a conveyor and delivered to a bale breaker. This opens the bales and ensures the RDF is liberated and blended before feeding into the drier (Materazzi *et al.*, 2019).

2.6 Global uses of RDF

The sections below provide some examples of RDF usage in countries such as Germany, Italy and South Africa.

2.6.1 Use of RDF in Germany

In Germany until 2005, landfilling was an option available for waste disposal. Before the landfill ban was approved in 1993, almost no RDF was produced in Germany. Between 1993 and 2005, the regulatory framework was complemented by a set of recycling regulations, and the SRF/RDF production received increasing support (Gallardo *et al*.2014). Germany has a well-developed waste management infrastructure, with a strong emphasis on recycling and waste-to-energy technologies. RDF plays a significant role in the country's waste management hierarchy, where waste is first prioritised for prevention, recycling, and composting, followed by energy recovery processes such as RDF. Cement plants in Germany have adopted co-incineration practices, where RDF is burned alongside traditional fuels, such as coal or petroleum coke, in the cement kilns (Sakka *et al.*2006). This process reduces the reliance on fossil fuels and helps in the sustainable management of waste.

2.6.2 Use of RDF in Italy

In Italy, RDF is co-fired with coal through pulverised co-firing. RDF co-firing in a pulverised coal unit requires only moderate additional investment, resulting in an average amount of waste in the fuel mixture. An example of this option is ENEL’s Fusina Power Station close to Venice, Italy, where RDF is introduced into the furnace of an existing PC boiler through coal burners (Vainika *et al.*, 2013). The Fusina plant has four units, where two of the units co-process RDF with coal through dry-bottom boilers. Since 1974, these units have each produced 320 Mwe, and their steam values are 538°C/178bar. The boilers are equipped with a low NOx concentric firing system, selective catalytic reduction, electrostatic precipitator (ESP) and flue-gas desulphurisation (FGD) plant burners (Vainika *et al.*, 2013)

2.6.3 Use of RDF in South Africa

The South African legal framework for WtE and RDF usage is outlined in Section 2.3.2 of this dissertation. The country has a well-developed policy framework, which allows for the co-processing of waste through the NEMWA and the NEMAQA, through authorisation processes. South Africa's policies on transitioning from coal to a more sustainable energy mix, which also includes alternative fuel sources also encourage the use of MSW as RDF (see Section 2.3.2 and its sub-sections).

The new climate-conscious South Africa saw its first RDF processing plant by Interwaste Holdings in Germiston, Gauteng, in 2014. Interwaste Holdings produces RDF with a calorific value of at least 24 MJ/kg. In South Africa, RDF has been tested in some cement kilns, but not every kiln is equipped to process RDF due to the infrastructural requirements of cement kilns (Oliveira, 2016).

The sections below reflect on the use of RDF in cement production, while also reflecting on the suitability and requirements of RDF for cement production purposes.

2.7 Use of RDF in cement production

RDF use in cement kilns has been practised in many countries since the 1970s (Sakri *et al.,* 2019, 2013; Velis *et al*., 2010). Through research, RDF has been bestowed as a solution to effect the change in global warming potential (GWP) of Ordinary Portland cement production and affected waste management systems in different municipalities (Khan *et al.,* 2020). Inherently, cement production is relatively energy-intensive and accounts for 30 to 40% of cement production costs (Bourtsalas, 2018). In a modern cement plant, that accounts for 30% of the total CO_2 emissions from the combustion of fuels in the kiln (Bosoaga *et al*., 2009).

In 2000, global CO_2 emissions from cement production were approximately 829 million metric tonnes of CO_2 ($MMTCO_2$), constituting at least 3.4% of the worldwide CO_2. Regressively in 2016, global cement production generated about 2.2 billion tonnes of CO_2, accounting for about 8% of the global CO_2 emissions (Andrew, 2018; Rodgers, 2018). The research further supports the findings by Mahasenan *et al*. (2003); in their conclusions, CO_2 content in cement production derived from energy consumption is about 0.85 to 1.35 tonnes of CO_2 per tonne of clinker; for every tonne of cement, 900 kg of CO_2 is produced.

The average energy demand to make one tonne of cement is about 17 to 18 MJ/kg, corresponding to 120 kg coal with a calorific value of 27.5 MJ per kg (Gallardo *et al.,* 2014). However, the calorific value of RDF is significantly less than that of coal, meaning that more RDF has to be burned to compensate for the energy equivalent of the coal it replaced (Lacovidou *et al.,* 2018).

Although RDF has the potential to replace or supplement coal, there are several aspects to consider for the use of RDF for cement manufacturing (Stubbs, 2016):

- Handling properties of the RDF;
- Ability to control the temperature in the kiln (or pre-calcining furnace);
- Effect of RDF combustion products on kiln coatings;
- Effect of RDF combustion products on clinker chemistry;
- Changes in physical properties of clinker and cement;
- Effect of using RDF on air emissions; and
- Infrastructural requirements for using RDF in cement kilns.

Section 2.7.1 discusses examples of how RDF has been successfully used in cement production, while Section 2.7.2 reflects on the suitability of RDF in cement production, addressing the complexities mentioned above.

2.7.1 Examples of early RDF use in cement production and lessons learned

Table 2-4 provides an overview of the use of RDF in cement kilns from 1974 to 1978. The considerations for the use of RDF are also outlined, highlighting the complexities of RDF usage for cement production.

Table 2-4: **Historic use of RDF as a kiln fuel (NCRR) National Centre for Resource Recovery, 1980**

Kiln name/location	Year	Results
Penn-Dixie Cement, Nazareth, National Recovery corporations	1974	Coal and Fluff RDF (7000 BTU/lb), where a 20% RDF to 80% coal ratio was employed. The fuel was best fed separately. The chemical and physical results showed a satisfactory clinker quality
Riverside Cement CO, California; Vista Chemical & Fiber Products Co.	1974	The kiln fed fluff with (5600 BTU/lb.) at a 20% to 80% fuel ratio. RDF replaced natural gas. At a 40% RDF ratio, feeding and temperature maintenance challenges were experienced.
Blue Circle Group Associated Portland cement manufacturers, Westbury, UK	1977	14 % RDF AND 86% coal mix at 7,000 TPY. Results showed acceptable clinker quality
Brownies Ferries Industry, Gulf Coast, Houston, Texas	1977	Shredded air classified used up to 20% - 30% RDF. Under burning, problems occurred at 40% RDF and 60 % coal fuel mix. This resulted in a reduction in cement strength and a rise in particulate emissions but within EPA standards
Blue Circle group Plymstock, UK	1977-78	Crude refuse must be pulverised to less (50 mm) in size to ensure complete burnout. RDF lends itself well to being blown in pneumatically through the kiln hood in the burning zone. Control of primary fuel and raw materials can compensate for variations in RDF. Although lead, zinc, copper, phosphate, and arsenic levels in clinker increased, cement quality was not substantially influenced by RDF use

Table 2-4 shows that RDF needs to be utilised in a highly controlled process. The National Centre for Resource Recovery (1980) concluded that because RDF are different from conventional fuels, cement kilns need to be modified to accommodate RDF. A particular comparison is that RDF is composed of fibrous-like material (shredded MSW) and in the form of a “thin plate”. Coal, on the other hand, is more crystalline, primarily spherical.

The 1974 Riverside trial showed that beyond 40% use of RDF, more feeding challenges and temperature control issues were encountered. Quality issues were similarly faced in the 1977 trial by Brownies Ferries Industry, where an RDF ratio beyond 40% reduced the cement’s strength, while particulate emissions were also an undesirable outcome. It is imperative to note that RDF is derived from different municipal solid waste and composed of different carbon-based organic forms. Hence, much attention needs to be considered in RDF’s chemical composition, especially because clinker directly interacts with fuel (Streier *et al. 2023*).

Furthermore, temperatures in the clinkering zone are strictly controlled by +/- 55 degrees Celsius. By definition, clinker is the Portland cement powder as we know it. This product is achieved by mixing raw materials of calcium, silica, alumina and iron oxide (Karstensen, 2007; Kaddatz *et al.*, 2013).

Nowadays, RDF’s substitution rates have improved much, which is shown by a rise in the countries co-firing RDF in cement production. Some good examples are Austria, Germany, other European countries (European Union), the United States and Canada (see Figure 2-7) (Sarc *et al*., 2013).

The sections below discuss the suitability of RDF in cement production and considerations for the use of RDF in cement production.

2.7.2 Suitability of RDF in cement production

RDF is used as an alternative fuel in cement kilns because of their (mostly suitable) physio-chemical properties. The type of RDF fed to the kiln is determined by the technical limitation of the kiln and type of feed system (Štofová *et al*., 2021). This section will evaluate the relevance of the properties of RDF as a fuel in cement production.

2.7.2.1 RDF content and quality requirements

Moodley (2016) states that the following questions should be considered before allowing the use of RDF in cement plants:

- What types of wastes are suitable for use in the cement manufacturing process?
- What process does the waste come from?
- What pollutants does the waste contain?
- What are the following characteristics of the waste: calorific value, water content, heavy metal content, chlorine content, etc.?
- Can the waste provider ensure consistent quality within a defined spectrum?
- What are the expected emissions from treating the waste?
- What harmful substances might result in the clinker or cement if the waste is used as fuel?

Furthermore, Khan *et al*. (2021) state that, if not appropriately sorted, the following chemicals will affect the kiln in the described manner:

- Phosphates may influence the setting time.
- Chlorine, sulphur, and alkali affect overall product quality.
- Chlorine at concentrations greater than 0.7% can affect the strength of the clinker.
- Chlorine can cause accelerated corrosion in the facility.
- Chlorine affects the overall quality of cement and concrete; and
- Chromium, which may cause allergic reactions in sensitive users.

2.7.2.1.1 Calorific value (CV)

As mentioned in the classification of the RDF section (Section 2.5.4.4.3), different standards can be employed to establish the same results. The quality aspect of RDF is primarily influenced by calorific value. MSW's average energy (calorific value) is approximately 10 MJ/kg; for example, plastics have 35 MJ/kg; textiles -19 MJ/kg; paper -16 MJ/kg; and organic materials – 4 MJ/kg, (Ismail *et al.,* 2020). These figures show that waste is a valuable energy source; however, getting the energy combinations correct is often challenging due to the complex nature of waste and the lack of resources and knowledge to use it as a fuel.

In developing countries like South Africa, MSW is characterised by its high moisture and organic content, which yields a low calorific value (Scarlat *et al*., 2015). To use MSW as an RDF in the cement industry, the calorific should have an uncompromised calorific value of at least 18 MJ/kg. This is because, furnaces where the pre-calciner reaction occurs require at least 1,700 MJ/tonne (Kaza *et al*.,2010). Therefore, a good RDF should be at least 18 MJ/kg. Table 2-5 compares the characteristics of coal versus RDF for parameters which are of significance for cement production.

Table 2-5: Characteristics of coal versus RDF Thirugnanam, Ganesh & Prakasam, Vignesh. (2013).

Characteristic	Coal	RDF
Calorific value (Kcal/kg)	4000	3500-3700
Equivalent tonne in calorific value	1	1.14
Sulphur content (weight %)	0.4	0.2 - 0.5
Moisture content (weight %)	39	10
Ash content (weight %)	4.2	< 15
NOx content (weight %)	1.2	1 – 1.5
Carbon (weight%)	31.4	35 – 40
Oxygen (weight %)	7.4	25 – 30
Hydrogen (weight %)	4.3	5 – 8

As shown in Table 2-5, RDF can compete with coal to heat the kiln and in some cases, RDF offers more sustainability. If managed properly, RDF has fewer heavy metals than coal, hence it will emit less synthetic carbon and offer a significant cost saving (Hemidat *et al*., 2019). The difference in the calorific value needs to be constantly measured when using RDF because waste streams are not systematic. Moreover, the heating value is usually measured in units of energy per unit of weight: kcal/kg and kJ/kg or MJ/kg (Bajracharya *et al.,* 2016)

2.7.2.1.2 Moisture content

According to trials conducted (Table 2-4), the absolute substitution of coal for RDF is not technically possible because RDF needs some treatment to become ready to burn as a fuel. The lower the moisture content, the higher the heating value of RDF, which is favourable for a supplementary fuel. Therefore, RDF drying is essential to reach the desired moisture content which is the main target of this project (Asadi, 2016).

Moisture content is typically measured using the net weight % of samples. According to the ISO standard ISO 21656 (2019), dry matter is analysed by placing samples in a preheated furnace set at 105 ˚C for 24 hours, and calculated through the following equation:

Dry Matter (W) % = (Dry sample weight/Wet sample weight) x 100%.

Dry matter or moisture content can also be evaluated using the European standard EN 15414-3 of 2011 or the ASTM standard (Ilham, 2022).

2.7.2.1.3 Heavy metal and Elemental content

When practising thermal treatment of waste in the form of MSW or RDF, heavy metal species may change their physical and chemical form. Although heavy metals are inert and give off no energy when they are incinerated, the high temperatures of an MSW furnace cause metals to be partially volatile, resulting in the release of toxic poisonous fumes, fly ash, and in some amounts be released to the atmosphere together with small particulate matter.

The metals of concern are cadmium (Cd), arsenic (As), lead (Pb), chromium (Cr), mercury (Hg), nickel (Ni) and zinc (Zn) (Hegazi *et al*., 2016). These metals result in harmful residues in fly ash, bottom ash, and hazardous emissions such as dioxins, toxins, nitrogen dioxide (NOx), sulphur dioxide (Sox), and harmful process residues (Hegazi *et al.,* 2016). After thermal treatment, the residue is bottom ash or fly ash. These residues are prone to enrich not only heavy metals in high concentrations but also dioxins, which are highly toxic and powerful carcinogenic organic pollutants, thus posing serious risks to the environment and humans.

2.7.2.1.4 Ash content

Bottom ash is an inevitable by-product of municipal solid waste (MSW) combustion plants. Incineration of MSW in WtE plants generates approximately 25 wt% of ash consisting of more than 90% bottom ash and 10% fly ash (Al-Rahbi *et al*, 2019). Bottom ash is considered inert but fly ash and pollution control residues are hazardous. However, unlike in WtE, heavy metals and chlorine are the main limiting factors because of the potential environmental risks and corrosion of cement kilns (Wu *et al*., 2016).

The chemical composition of MSW ash has been extensively researched. Zaini *et al* (2019) proved that plastic has lower ash content than coal, and ash content has an inverse relationship with heat value. Their research hypothesis supported that fuel with ash content from 10% to 25% should be used. Conclusively, a fuel with an ash content higher than 40% should be rejected.

Another chemical of concern from ash is chlorine. Some studies, however, proved that ash is not a significant source of chlorine, but rather flue gas contains more chlorine. A definitive reference is Wang *et al*. (2019), who studied the composition of chlorine between flue gases and ash. The chlorine content in the flue gas was determined using ion chromatography. High-temperature combustion hydrolysing-ion chromatography measured the chlorine content in fly ash and residual solid. The results showed that chlorine mainly existed in flue gas and residual solid, and only less than 3.5% of chlorine existed in fly ash. Furthermore, and on the chemical aspect of classifying ash as a hazardous material, another common undesired element of ash are heavy metals, especially Cr and Pb in bottom ash (stu. 2016) as discussed in Section 2.5.2.1.3 above.

2.7.2.1.5 Chlorine content

Chlorine is widely dispersed among various chemical compounds in several waste items, especially PVC. Understanding chlorine sources and thermal behaviour is imperative to make RDF production sustainable. Zaini *et al.* (2019) covered a wide range of chlorine sources and reviewed that chlorine content ranges from 0.1. wt.% in wood, to greater than six wt.% in sources such as non-packaging plastics (dry basis), polyvinylchloride (PVC) from packaging, electrical wire insulation etc. Plastics and chloride salts (mainly NaCl) in kitchen waste are organic and inorganic chlorine sources.

These findings contribute to understanding the thermal behaviour of chlorine in RDF, waste-to-energy plants and all other alternative fuel combustion processes. Such awareness leads to suggestions for fuel management for waste-derived fuels to avoid chlorine-induced corrosion. The variability around mean Cl in SRF is at 36.7% (CV), notably lower than that in MSW, indicating effective variability reduction because of the mechanical processing of MSW into RDF (Gerassimidou *et al.,* 2021).

2.7.2.1.5.1 Effects of chlorine on cement production

During co-combustion, most Cl remains within the kiln system causing operating problems, and only a tiny percentage (0.7 to 13%) is incorporated in the clinker, making it stickier. The air pollution control system captures a significant proportion. State-of-the-art engineering practices can result in reasonable SRF quality assurance, essentially preventing Cl-related problems in the kiln. Further investigation on the impact of fuel feeding systems, the effect of Cl speciation, and controlling the sources of Cl variability are needed to improve confidence in SRF uptake. The presence of chlorine in waste fuels can, directly and indirectly, affect cement kiln emissions and performance. The main problem regarding the use of RDF by cement kilns is the chlorine content. When the chlorine content is high, it weakens the concrete in terms of two-, seven---, and twenty-eight-days compressive strength (Kara *et al*., 2011). The chlorine compounds and alkali-silica reactions create salts. These salts generate microcracks and the compressive strength decreases (European Committee for Standardization [ECS], 2002a) (Keiser *et al*., 2022). Also, chlorine creates the oxidation of iron in concrete.

The cement industry's chlorine (Cl) acceptance standard is 1000 mg/kg, with zinc (Zn) at 1700 mg/kg, and chromium (Cr) at 170 mg/kg (Hollins *et al*. 2017).

Trace levels of chlorine in feed materials can lead to the formation of acidic gases such as HCl and HF (Murray et al., 2008). Chlorine compounds can also build up on kiln surfaces and lead to corrosion. Introducing chlorine into the kiln may also increase the volatility of heavy metals (Murray *et al.,* 2008) and foster the formation of dioxins. Genon and Brizio (2008) indicated that the alkaline matrix of the clinker means that the presence of chlorine in substitute fuels does not result in critical levels of gaseous emissions.

2.7.2.1.6 Fuel carbon content

To successfully lower CO_2 emissions in cement factories, kilns must minimise the fossil carbon content of the fuel, e.g., shifting from coal to natural gas or to AF, such as RDF, which presents a lower carbon content (Reza *et al.,* 2013). The amount of CO_2 emitted during this process is influenced by the type of fuel used (for instance: coal, fuel oil, natural gas, petroleum coke, AF). The relative CO_2 emission factors (EF-CO_2) are defined by the (IPCC) Inter-Government Panel on Climate Change (Psomopoulos *et al.,* 2015). As per IPCC standards, the direct EFCO_2 of waste fuels is estimated to be less than coal because waste input has a biogenic fraction that dilutes an equivalent amount of fossil fuel-derived energy. RDF, however, needs to be as consistent as possible as a fuel to replace coal.

RDF which is densified has been researched to have the least CO_2 emissions with 1.696 kg CO_{2}-eq (Nutongkaew *et al.,* 2014), while coal has an emission factor of at least 34 kg CO_{2}-eq. RDF as a substitute or co-fuel may, thus, significantly lower the carbon emissions in cement co-processing, when compared to using coal only.

The need for standardisation of synthetic and biogenic carbon in RDF is imperative, especially in areas where a specific market for RDF is currently under development or emissions standards are to be considered (Vounatos *et al*., 2016). Fixed carbon is the relative part of carbon contained in a material that can only be degraded at high temperatures (ISO 21656, 2021). Carbon can either be synthetic or biogenic, depending on the source. The biogenic carbon content of the fuel can be measured using ISO 21656 for solid recovered fuels (Omar *et al*., 2021). While synthetic carbon can be measured using the carbon-14 analysis method (Gershon *et al.,* 2019).

2.7.2.1.7 Sulphur content

The largest source of sulphur dioxide (SO_2) in the atmosphere is the burning of fossil fuels by power plants and other industrial facilities such as cement production (EPA, Environmental Protection Agency, 2022). In cement production, the concentration of sulphur in substitute fuels is generally much lower than the reference value in conventional fossil fuels (0.1 - 0.2% in RDF, 3% - 5% per cent in fossil fuels). Although the ability of cement kilns to remove sulphur dioxide (SO_2) from exhaust gases, there are limits on the amounts of sulphur which can be acceptably incorporated into the clinker.

ASTM Standard C-150 sets an upper limit of 3% to 3.5% sulphate in cement, depending on the level of tricalcium aluminate in the clinker (Churney *et al*., 1985). Excessive sulphate levels in cement have been associated with a condition known as efflorescence (NCRR, National Centre for Resource Recovery,1980).

Furthermore, alkali sequestration and transfer issues in the clinker must be assessed (Genon and Brizio 2008). This is because clinker has an alkaline matrix, and sulphur might react with different metals. Considering the atmospheric implications of sulphur, gaseous sulphur oxides (SOx) can harm trees and plants by damaging foliage and decreasing growth. However, in cement kilns, alternative fuel use does not increase relative emissions of sulphur dioxide as stated in the baseline monitoring by the DFFE (GNR.777, 2009) (Young, 2020).

2.7.2.2 RDF pre-calciner feeding.

When rotary kilns were inverted, the technology used a wet process. The introduction of modern drying process optimisation led to technologies that allowed drying pre-heating and calcining in stationary installations, such as the pre-calciner (Karstensen, 2007).

Even today, cement manufacturers use dry and wet fuels such as municipal solid waste, sewage sludge, and other alternative fuels to replace fossil fuels (Herrero & Vilella, 2018). Different kiln processes use these fuels with varying heat requirements at different feeding points (Wojtacha-Rychter *et al.,* 2021). Industrialised countries have more than 20 years of successful experience with the co-processing of wastes in cement production. Murray *et al,* (2008) indicated that alternative fuels are essential to their continued competitiveness if modelled correctly through a proper understanding of their physiology.

According to Asadi (2016), the following are the relative cement kiln feeding points:

- Through the main flare in the oven and exit (powder fuel).
- through feed shooter in transfer chamber in oven end entrance (piece fuel).
- through pre–calciner to pre–calciner flares (powder fuel); and/or
- through feed shooter to pre–calciner (piece fuel).

Asadi (2019) reiterates that the RDF fed at each feeding point is regulated. Therefore, the kiln may be affected if the feeding point is blocked. Table 2-6 shows the regulated percentage feed rate at each feeding point). Given the differences in temperature in different parts of the cement production process, waste materials must be introduced at the correct point (feed point) to ensure complete combustion or incorporation and avoid unwanted emissions (Anasstasia *et al*., 2020). The feed point should be selected according to the nature of the waste fuels. The most common points at which wastes are inserted into the cement production process are (Karstensen, 2004)

Table 2-6: Regulated alternative feeding rate per point (Karstensen 2004).

Feed point	**Liquid alternative fuel %**	**Fine solid alternative fuel %**	**Course solid alternative fuel %**	**Lump alternative fuel %**
Main Firing	Up to 100	Up to 30	-	-
Kiln Inlet firing and secondary firing	Up to 15	Up to 15	Up to 15	Up to 15
Pre-calciner	Up to 60	Up to 60	Up to 60	-

All materials (RDF) introduced into a cement production process should ideally resemble the homogeneity, particle size distribution, heat and water content and chemical composition of ordinary fine coal and raw meal used in cement manufacturing (Hajinezhad *et al.*, 2016).

2.7.2.3 RDF and cement kiln readiness

The modern Portland cement manufacturing technique was invented in 1895, and very little has changed since the move to rotary kilns (Kaddatz *et al*., 2013); (Karstensen, 2007). Rotary kilns have become familiar and are well-understood around the world. The modern-day rotary kilns face a universal problem in the energy requirements to start the pre-calciner. In their respective studies, Herrero & Vilella (2018) and Wojtacha-Rychter et al. (2021) researched that Portland cement is energy-intensive, with the furnaces requiring temperatures between 1450°C to 1500°C for ignition to occur. The reaction has an uncompromised calorific value requirement of 1,700 MJ/tonne. As a result, 40% of the greenhouse gas emissions are in the rotary kiln.

It has been demonstrated that RDF co-processing can be accomplished environmentally soundly. However, although cement kilns have all the desirable properties for efficient thermal destruction of many hazardous wastes, not every cement kiln can utilise RDF (Paszkowski *et al.,* 2020). Many cement kilns were not designed for this purpose and require modification of the fuel injection system and construction of waste-receiving facilities (Reza *et al*., 2013). These facility modifications should be carefully designed and monitored to minimise environmental and health risks (Karstensen, 2007). Alternative fuel requires a compatible dosage feed system, a storage facility, conveyance, measurements, and emissions control. Different fuel dosing systems can be used depending on the waste fuel feed point. Any type of feeding system used should ensure high accuracy and consistency, avoid breakdowns caused by blockages, and flexibly accommodate a range of fuels.

2.8 Carbon reduction benefits of using RDF for cement production

Several studies have extensively researched the environmental impact of utilising alternative fuels in cement plants. These studies have conclusively ascertained that fossil fuels need to be optimised for sustainable cement production; Georgiopoulou & Lyberatos, 2018; Benhelal &Rafiei,2012). In addition, Güereca *et al*. (2015) and Helftewes *et al.*, (2012) stated that Solid Recovered (2017) Fuel is the best source of high calorific value fuel with a calorific value of at least 24 MJ/kg.

Despite RDF utilisation significantly impacting CO_2 emissions, certain aspects of RDF need to be understood. First, the heating value of the RDF depends on the composition of waste, subsequently affecting the CO_2 emission factor. Waste fractions with high carbon content (plastics) usually have higher heating values than fractions with higher biogenic carbon content (wood and paper) (Khan *et al*.,.2020). Therefore, RDF with higher heating values also has higher CO_2 emission factors and vice versa. On the other hand, using fuel with a lower heat value means more fuel is required to provide an equal amount of fuel energy to RDF with a higher heating value. Therefore, using more synthetic carbon fuels lowers the benefit of a lower CO_2 emission factor. This comparison shows that what often gets overlooked is that conventional plastic is made from fossil fuels and is a product of the oil and gas industry (Nielsen *et al,* 2020). Making plastics involves exposing extracted oil and gas to enormous amounts of heat and pressure to create the building blocks of polymers, for example, natural gas or crude oil propane propylene, polypropylene, for example plastic cups (Schunck, 2022). Several bio-based plastics made by converting the sugar present in plants into plastic, have been developed. However, they still only account for less than one per cent of the market, which remains entirely dominated by fossil fuel-based plastics.

Furthermore, according to the 2006 International Panel on Climate Change (IPCC) guidelines, organic waste is excluded from municipal solid waste inventories. They are instead listed under the Agriculture, Forestry and Other Land Use section to avoid double-counting. Agencies such as the Environmental Protection Agency in the United States have recommended that biogenic carbon emissions be counted when assessing emissions from particular waste or energy facilities (Environmental Protection Agency 2010). In a global sense, carbon neutrality means net zero emissions of anthropogenic CO_2 (Eloka- Eboka *et al.,* 2020). In the context of thermal WtE, CO_2 released from biomass combustion is assumed to be offset by the CO_2 initially absorbed through photosynthesis. Emission credits for the use of non-fossil waste as a substitute for fossil fuel are also calculated as part of carbon neutrality. The carbon neutrality assumption is being challenged by a growing number of experts (Liu *et al.* 2017; Cherubini *et al*. 2011) who have assessed the global warming potential of biomass-associated combustion. Researchers have also highlighted that human activity has profoundly altered the natural carbon cycle in a way that exacerbates climate change, in particular, due to impacts from the timing of anthropogenic biogenic carbon emissions (Searchinger *et al*., 2009; Elok-Eboka *et al*., 2020; Levasseur *et al*., 2013. Biomass may take many years to regrow to the point where it absorbs the biogenic CO_2 emitted from thermal treatment.

2.9 Chapter summary

This chapter has reviewed different findings in the form of cross-sectional and time series data from other researchers that have enabled the use of RDF in co-processing fuel in cement kilns.

In areas where fuels have been successfully implemented, a supportive policy framework has been implemented first, followed by meaningful investment in waste management infrastructure. Using RDF as a fuel requires an enabling environment where one is no less important than the other. RDF is not a one-size-fit solution in cement kilns, but investment in knowledge and infrastructure will change the narrative, especially for African countries.

The following chapter will address the research methodology followed in pursuit of the research aim.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter outlines the research design, research paradigm, data collection and analysis techniques applied during this research. The chapter also reports on data reliability and validity, research assumptions and limitations, before closing the chapter with ethical considerations applicable to this research.

3.2 Research paradigm and approach

The systematic quest for knowledge can be considered through different research paradigms that make assumptions about how the world operates. These research paradigms are the core and mainspring of scientific research by shaping the following macro-elements: ontology (how reality is perceived), epistemology (how the nature of knowledge is understood), axiology (the role and values of all research processes), methodology (how the paradigm defines processes associated with conducting science), rigour (the criteria used to justify the quality of research in the paradigm) (Park *et al*., 2020) and experimental design. This research followed the positivism paradigm through experimental design.

The positivism paradigm relies on the hypothetic deductive method to verify a priority hypothesis that is often stated quantitatively, where relationships of variables can be derived between causal and explanatory factors (independent variables) and outcomes (dependent variables) (Ryan, 2015). The positivism paradigm was adopted because the author subscribes to the notion that research findings must be concluded based on scientific and objective findings, which requires that presented data must be precise, verifiable, systematic, and theoretically answer the research aim and objectives. The positivist way of scientific investigation supports that knowledge is gathered using science (experimental design) based on results gained through primary experiments or comparative analysis. By developing scientific facts, knowledge is built up cumulatively (Sileyew, 2020). In an experimental design, a researcher will introduce an independent variable and measure the impact it has on the dependent variable in order to draw conclusions about causality and correlations between the two. The goal is to collect data that can be objectively observed and measured in order to draw valid, reliable, and generalisable conclusions from the results.

The research employed a mixed methods approach where both quantitative data (through laboratory experiments) and qualitative data (through survey questionnaires) were collected (refer to Table 3-1). Experimental research attempts to isolate and control every relevant condition, determining the events investigated and observing the effects when the conditions are manipulated (Barry *et al.,* 2019, Walliman, 2011).

3.3 Research design

The following sections describe the research design which informed data collection related to the three research objectives. The research design is outlined in Table 3-1.

Table 3-1: Research design

Research objective	**Data collection**	**Justification**
Research objective1: To analyse the physio-chemical properties of Refuse Derived Fuel (RDF) for cement production	RDF samples of different waste compositions are tested using ASTM-D7582 to analyse their physio-chemical properties such as calorific value, dry matter and ash content, heavy metals and volatile matter.	This study measured RDF as a function of calorific value, moisture, carbon content, dry matter, and heavy metals content. The researcher used the ASTM standard as it is generally applied for physio-chemical testing in South Africa, less expensive, accessible, and dependable. ASTM standards promote interlaboratory comparability, allowing different laboratories to obtain similar results when testing RDF samples. This comparability is essential for regulatory compliance, trade, and research purposes, as it ensures that measurements are not biased by the testing facility or methodology (Pitak *et al*., 2022).
Research objective 2: To optimise the carbon benefit of RDF as a fuel in cement processing	Three samples with different biogenic carbon to synthetic carbon ratios are analysed to determine the RDF waste ratios that will provide the optimum conditions for cement manufacturing, based on the technical and operational efficiency.	This objective aimed at reducing intersectoral CO_2 emissions between cement production and waste management. This RO considers fuel ratio (paper: plastic ratio), net calorific value (CV), synthetic CO_2-eq per tonne (relative to coal) and, ultimately, CO_2 saved per tonne (%) (relative to coal).
Research objective 3: To investigate the opportunities and challenges for using MSW as RDF in cement production.	Structured survey questionnaire distributed to South African cement manufacturing professionals.	In this research, surveys were used as they are easier to analyse statistically. The structured and semi-structured format of survey questionnaires allows for straightforward data coding and entry, facilitating data analysis and comparison across different variables (De Franzo, 2012).

3.4 Data collection

As explained in Table 3-1, data was collected through a combination of experimental analysis (for RO1 and RO2) and a survey questionnaire (RO3). The next sub-sections will describe the data collection methods employed for this research.

3.4.1 Analysis of the physio-chemical composition of RDF (RO1)

Objective one of the research focuses on determining the physical and chemical properties of RDF. The data in this section is collected through laboratory analysis. Figure 3-1 provides an overview of the steps followed to prepare the MSW samples before laboratory analysis.

3.4.1.1 Sample preparation

Municipal solid waste (MSW) consisting of non-hazardous plastic and paper waste were used for the analysis. Figure 3-1 provides an overview of the RDF sample preparation before analysis.

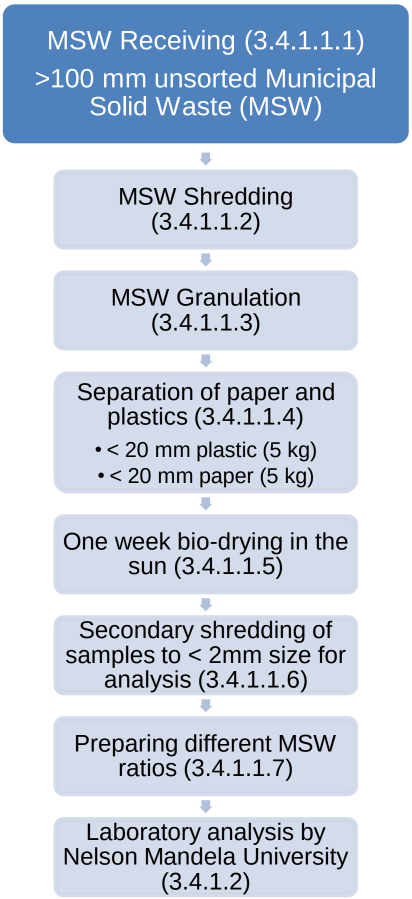

Figure 3-1: RDF Sample preparation method

The processes outlined in Figure 3-1 are elaborated on in the sub-sections below.

3.4.1.1.1 Municipal Solid Waste (MSW) receiving

Municipal Solid Waste (MSW) was received at the Interwaste RDF plant as shown in Figure 3-2. The feedstock consisted of pre-consumer waste from food processing and packaging companies. The first step of this mechanical treatment process is shredding (Section 3.4.1.1.2), where plastic waste and paper waste are sorted manually and shredded separately.

Figure 3-2: RDF Sample preparation method

3.4.1.1.2 MSW shredding

The next step involves mechanical downsizing of the solid waste, called shredding. This process reduces the surface area of the feedstock to allow improved surface area for drying. When received, the MSW will be over 100 mm in size. Shredding facilitates size reduction to well below 50 mm in particle size. Figure 3-3 below shows the input conveyor to the shredder and the shredder utilised for the research.

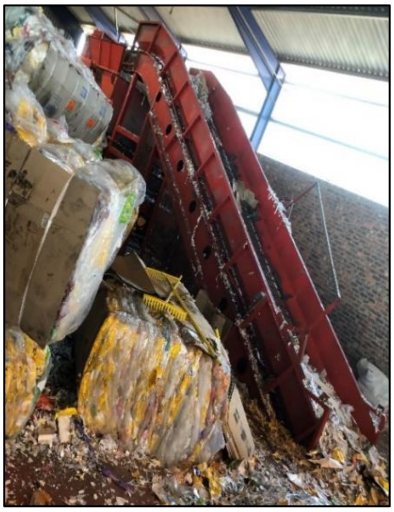

Figure 3-3: Shredding of MSW

3.4.1.1.3 MSW granulation

To further reduce the size of MSW and provide a uniform sample, a granulator was used. Granulation assists in downsizing smaller materials that cannot be shredded due to their size. The process has a sieve that only allows smaller material to pass through and larger particles are granulated until they are fragmented to smaller sizes (<20 mm) that can pass the granulator sieve. Figure 3-4 below shows the output conveyor of the granulator with the granulated products.

Figure 3-4: Granulation of MSW

3.4.1.1.4 MSW separation

Separated 5-kilogram samples of plastic (representing the synthetic content of the RDF) and 5 kilograms of paper (representing the biogenic content of the RDF) were subjected to drying.

3.4.1.1.5 MSW bio-drying

The concept of drying is meant to make use of thermal evaporation from the sun. MSW usually has moisture that is not feasible for RDF efficiency. The MSW was dried on a concrete floor using an open plastic receptacle as shown in Figure 3.5. The process was done for one week during the day (8 hours) from 08:00 to 16:00.

As supported by Zaman *et al.* (2021), the researcher concluded that bio-drying is influenced by external factors below.

Bio Drying= Humidity, + Temperature +Air/wind velocity.

Figure 3-5: Drying of MSW

3.4.1.1.6 Secondary shredding of MSW

After drying, the samples were sent to an accredited laboratory at Nelson Mandela University for further processing and analysis. The samples were shredded to a size of 2 mm before examination.

3.4.1.1.7 Preparing different MSW ratios

Based on research by Chatziaras *et al*. (2016), Bourtsalas *et al*. (2018) and Rezaei *et al.* (2020), utilising 100 % paper as RDF will not exceed a calorific value of 14Mj/kg, while utilising 100% plastic will not be environmental efficiency. To strike environmental and operational efficiency, the following three RDF samples were prepared to provide for both synthetic (plastic) and biogenic (paper) carbon in different ratios:

- Sample 1: 60% paper to 40% plastic.
- Sample 2: 40% paper to 60% plastic; and
- Sample 3: 50% paper to 50% plastic.

Although other sources of MSW could also be suitable for energy recovery, the research focused on paper and plastic waste only as a source of RDF, because the characteristics of paper and plastic waste such as low moisture content by weight, high volatile matter, and calorific value can technically substitute coal as a fuel (Kungkajet *et al.*, 2015). Furthermore, just like coal emissions, plastic and paper present synthetic and biogenic carbon, respectively. Additionally, both plastic and paper are waste streams that are suitable for incineration and diversion from landfill sites; it can be easily separated from other waste streams; and are abundant waste streams in the South African context. While solid waste disposal in South Africa results in the emissions of anthropogenic gases such as methane and CO_2, plastic on its own is a fossil fuel that brings environmental compliance concerns to the cement kilns (Ali *et al*., 2023). Paper is a biogenic source with a higher CV that is technically efficient in cement kiln combustion.

The three samples were prepared by using a calibrated laboratory scale. According to Nelson Mandela University's requirements, three sets of 1 mm samples were prepared.

3.4.1.2 Laboratory analysis of samples

Quantitative research, by definition, can be classified as the utilisation and analysis of numerical data using specific statistical techniques to answer questions like who, how much, what, where, when, how many, and how (Apuke, 2017). In this experimental research, physical and chemical analyses of the MSW were evaluated by an accredited laboratory at Nelson Mandela University. The physical properties evaluated included dry matter analysis, ash content, and heavy metal analysis. Furthermore, RDF is promoted as environmentally sustainable and as operationally efficient as coal. To determine the chemical characteristics of the feedstock, calorific value, carbon content and chlorine content were analysed.

The physical and chemical analysis of the sample utilised ASTM-D7582 standard *"Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis"*. This instrumental test method covers the determination of moisture, volatile matter, and ash, and the calculation of fixed carbon, traditionally in the analysis of coal and coke samples, prepared in accordance with Practice D2013 and Practice D346. For the purposes of this research, the test method was used to analyse MSW, as a potential substitute for coal in cement production.

3.4.1.2.1 Analysis of dry matter/moisture content

Dry matter was analysed in accordance with ASTM-D7582 by placing the prepared samples in a pre-heated furnace. Dry matter was measured three times per sample after reporting the wet and dry weights. Dry matter for each sample was then obtained through the following equation:

$$\text{Dry Matter (W) \%} = (\text{Dry sample weight}/\text{Wet sample weight}) \times 100\%$$

3.4.1.2.2 Analysis of ash content

Ash content has an inverse relationship with heat value. The higher the ash, the lesser the heat value (Akaki *et al.,* 2012). The Ash content of the original material and the total solids were analysed by burning the samples. Ash yield or ash content is the residue remaining after heating the MSW sample. The ash content was calculated following ASTM-D7582 by taking the residual mass after heating into consideration. Ash content of the prepared samples was measured three times per sample and the average was taken.

3.4.1.2.3 Calorific value analysis

Calorific value analysis was done according to ASTM-D7582. Calorimeters provide a simple means for measuring the heating values of fuels. Two basic types of calorimeters can be used to measure the heating value: a steady-flow calorimeter for gaseous fuels, and the bomb calorimeter (constant volume) for liquid and solid fuels. The adiabatic bomb calorimeter of (ASTM D5865 11a) was used for the purposes of this research. The heating value is usually measured in units of energy per unit of weight: kcal/kg and kJ/kg. The heating value for the samples was calculated three times per sample and the average value was taken.

3.4.1.2.4 Analysis of heavy metals

Heavy metals were analysed using the (ASTM D5865 11a) metal analysis test method to measure carbon C, nitrogen(N), hydrogen (H), and sulphur (S). This elemental analysis is vital to determine these metals especially when applying thermal treatments to the RDF. Furthermore, S, C, and N are considered the main causes of sulphur dioxide, CO_2, and nitrogen dioxide formation, which lead to the formation of photochemical smog at the nearest atmospheric layer to the ground "troposphere" and the greenhouse gases (Hemidat *et al.,* 2019).

3.4.1.2.5 Chlorine content analysis

Chlorine content was determined based on the European Standard (BS EN 15408) *"Solid recovered fuels. Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content"*. This standard specifies the determination of chlorine in solid recovered fuels of various origins and compositions after combustion in an oxygen atmosphere. As highlighted in chapter (subsection 2.7.2.1), it is imperative to control the chlorine levels of RDF since excessive chlorine can cause corrosion in the kiln (Khan *et al*., 2021).

3.4.2 Optimising the carbon benefit of RDF as a fuel in cement processing (RO2)

The second research objective aimed at optimising the carbon benefit of RDF as a fuel in cement processing. This objective aimed at reducing intersectoral CO_2 emissions between cement production and waste management. For this purpose, three samples with different biogenic carbon to synthetic carbon ratios were analysed to determine the RDF waste ratios that will provide the optimum conditions for cement manufacturing, based on net calorific value (CV), synthetic CO_2-eq per tonne (relative to coal) and, ultimately, CO_2 saved per tonne (%) (relative to coal).

As highlighted by Bras *et al* (2020), the partial replacement of a net carbon offset through replacing coal with RDF (with less than 15% of water) may reach a net reduction in emissions of 0.4 tonnes CO_2/tonne of RDF. The researcher aimed at further reducing the CO_2 emissions factor by acknowledging that using less plastics and more biogenic materials such as paper can optimise the carbon benefit of using RDF as a fuel in cement production.

3.4.2.1 Fixed carbon and carbon dioxide emission estimation

The solid carbon content or fixed carbon of each of the three RDF samples was determined through ASTM D5865. By definition, fixed carbon is the percentage of the fuel that is not volatile and comes from the organic source of the fuel (Wang *et al*.2021). Fixed carbon was then calculated based on moisture content, ash content and volatile matter (Anshariah *et al*., 2020, Lacovidou *et al.,* 2018) by using the following formula:

$$\text{Fixed carbon \%} = 100\% - ((\text{Moisture} + \text{Volatile Matter\%}) - \text{Ash\%})$$

Ultimately, the carbon dioxide equivalents per tonne of cement manufactured were calculated for each of the three samples by using the effective CO_2 emissions factor method, which estimates the CO_2 equivalent per mass.

3.4.2.2 Calculating the Effective CO_2 emission factor of RDF

Emissions of greenhouse can be determined on the basis of continual emission measurements, or by calculation. Continual measurements are to be considered only in places where standard pollutants are already being measured continually, however, even there it is necessary to verify the measurements by calculation. For the purposes of this research, calculations were used.

In order to calculate CO_2 emissions for stationery combustion systems such as cement production, the researcher utilised the direct emission factor method in accord with Decree No. 696/2004 otherwise known as the emission factor method for solid fuels, which can be expressed by the following formula proposed by Fott *et al*. (2006).

$$EF(CO_2) = (44/12)(C^r/Q)$$

Where:

- EF (CO_2) = Mass emissions of CO_2 tonnes per terajoule of energy,
- where C^r is the content of carbon in a raw sample of the fuel (i.e. in the fuel supplied),
- Q is the net calorific value of the fuel supplied,

- *(44/12)* represents the stoichiometric coefficient or the ratio of the molecular weight of CO_2 to that of carbon, and
- All total samples before combustion are 100 grams.

3.4.3 Investigating opportunities and challenges for using MSW as RDF in cement production (RO3)

To investigate opportunities and challenges for using MSW as RDF in cement production, a two-pronged approach was followed. Firstly, a literature review was used to identify opportunities and challenges based on existing research by others. Secondly, perceived opportunities and challenges were determined by using a survey questionnaire that was distributed to industry experts in the cement manufacturing sector. The information gleaned from the literature was used to compile the survey questionnaire. To investigate opportunities and challenges for MSW as RDF in cement production in South Africa, the researcher used information gathered from literature to evaluate and understand the (perceived) challenges and opportunities that professionals in the cement production sector are facing in the adoption of RDF as an alternative fuel.

3.4.3.1 Literature review

Chapter 2 reviewed the literature revealing how perception and experiences of utilising RDF in cement production have brought out different insights around the world in the form of opportunities and challenges. The literature review was conducted by examining the literature that could be accessed on Google Scholar, Scopus and ResearchGate, as well as the North-West University's (NWU) library website. Official government and other organisation documents that were applicable to the research where considered. Search words related to the study were used to find the relevant literature. The researcher was inspired by South African papers such as "*Cement production in South Africa and an evaluation of their Ability to Co-process AFRs and Hazardous waste"* by Karstensen (2007) and another paper by Moodley (2014) titled "*Waste-to-energy Can it be a solution to the waste puzzle''*. The papers included keywords/phrases such as "Municipal Solid Waste", "waste management", "co-processing", "biogenic carbon" and "refuse-derived fuel" in different combinations.

3.4.3.2 Survey questionnaire

As mentioned above, surveys were used to gather the perceptions of cement manufacturing industry experts on the opportunities and challenges of using MSW as RDF in cement production. The structured format of survey questionnaires allows for straightforward data coding and entry, facilitating data analysis and comparison across different variables (Greenhoot, 2012). Furthermore, survey questionnaires enable the standardisation of data collection, ensuring that all participants receive the same set of questions consistently.

3.4.3.2.1 Developing the survey questionnaire

The variables and their association (as depicted in Figure 3-6) informed the development of the survey questionnaire.

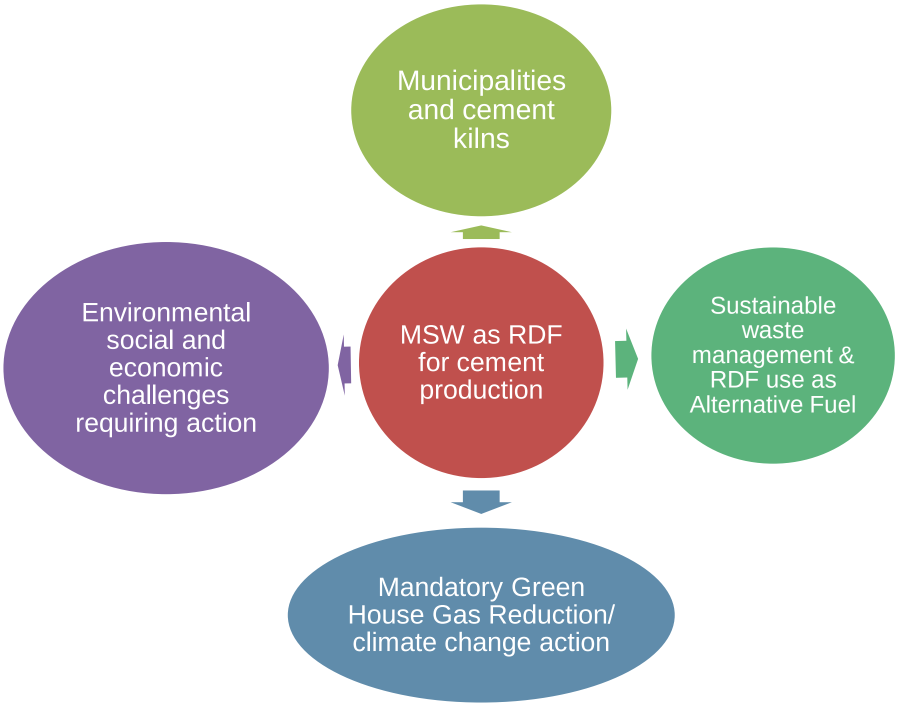

Figure 3-6: Variable informing the development of the survey questionnaire

A survey questionnaire was developed to address RO3. The survey questionnaire aimed to provide a holistic overview of the opportunities and possible setbacks in implementing the use if RDF in the South African cement production sector. The opening section of the survey introduced the research aim, background and ethical clearance obtained, and also required that participants provide informed consent before responding to the study. The questionnaire was set up in Google Forms for easy distribution and capturing of responses.

The first section of the survey questionnaire (Section 1) gathered background information from respondents, such as the name of their organisation (i.e., which cement manufacturer they were representing), the province where the cement producer is located, respondents' job profile/position in the organisation, their highest level of education, age and gender (Refer to Annexure A). Section 2 posed eight technology/operational questions, Section 3 posed six policy and licencing questions, Section 4 posed eight environmental questions, Section 5 posed six economic questions, and Section 6 concluded with two open-ended questions, where participants could freely express their perceptions on the opportunities and challenges of using MSW as RDF in cement production (Refer to Annexure A).

The questions posed in Sections 2 to 5 were posed as statements, where participants had to express their level of agreement with the specific statement. An ordinal (Likert) scale was provided to measure the level of agreement with each of the statements, where *1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree and 5 = Strongly agree*. The Likert scale provides a structured and standard way to measure subject constructs, making it practical to measure responses and consistently draw conclusions from data. In the context of this research, the benefits of a Likert scale are the relative responses can be quantified without limiting questions to technical responses only, but also factoring in attitudes, opinions, and the behaviour of respondents towards certain subjects.

3.4.3.2.2 Piloting the survey questionnaire

The questionnaire was piloted (pre-tested) by administering the survey to a small sample of respondents (environmental consultants and students) before distributing the questionnaire. The survey was sent to five persons (environmental consultants and students) to complete. The purpose of the piloting phase was to determine whether all questions were clear and understandable. Responses (on whether the questions were easy to understand and clear) from the pilot phase were used to update the survey questionnaire. Survey responses were disregarded and not used as part of the results of this research.

3.4.3.2.3 Selection of survey participants

A “sample” is a section of a broader population that will be engaged, usually for research purposes. The actual process of selecting that section/portion of the population, which is a small group of cases from a large area, is what researchers call “sampling” (Whitehead, 2016). It is identifying who in this large area best represents the characteristics of a given population. A successful sampling exercise is depicted by how accurately a sample size means the population in question is without bias (Cohen *et al*., 2007).

The researcher employed purposive sampling to select survey participants. Experts/professionals employed in the cement manufacturing sector were targeted as research participants. Cement producers in South Africa are listed by the Association of Cementitious Material Producers (ACMP). Due to the readily available data on cement kilns, purposive sampling accurately represents the total population. In addition, it utilises the best general knowledge concerning the sample subjects (Ragab *et al*, 2017).

The listed mainstream cement producers in South Africa include Afrisam, Lafarge (Geocycle), Natal Portland Cement (NPC)/Intercement, PPC Cement, and Sephaku Cement. Employees who work in the fields of production, process technology, environmental management, operations management, and/or quality management were targeted as respondents.

3.4.3.2.4 Distribution of survey questionnaires

For the convenience of the respondents, electronic copies (using a link to Google Forms) of the survey questionnaire were distributed via e-mail. The survey was sent to a total of thirty (30) respondents (refer to the selection of survey participants identified in Section 3.4.3.2.3).

3.4.3.2.5 Survey respondents

A total of twenty-two (22) participants responded to the survey questionnaire (response rate of 73%). Table 3-2 presents the background information of the respondents.

Table 3-2: Background information of respondents (n = 22)

Background information of the respondent	Number	% of sample
Name of organisation		
AfriSam	1	4.5%
PPC Cement	10	45.5%
Geocycle/Lafarge	5	22.7%
NPC/Intercement	4	18.2%
Sephaku Cement	2	9.1%
Province		
Gauteng	4	18.2%
Western Cape	6	27.3%
North-West	6	27.3%
KwaZulu-Natal	4	18.2%
Eastern Cape	2	9.1%
Position in organisation		
Processing/technology	4	18.2%
Production	2	9.1%
Operations	2	9.1%
Safety, Health and Environment (SHE)	6	27.3%
Safety, Health, Environment and Quality (SHEQ)	7	31.8%
Occupational Health and Safety (OHS)	1	4.5%
Highest qualification		
High School	4	18.2%
Bachelor’s degree	8	36.4%
Hons degree	5	22.7%
Master’s degree	5	22.7%
Gender		
Male	12	54.5%

Background information of the respondent	Number	% of sample
Female	10	45.5%
Age category		
21 - 30	6	27.3%
31 - 40	7	31.8%
41 - 50	9	40.9%

These participants represented five cement manufacturers (Afrisam, PPC Cement, Geocycle/Lafarge, NPC/Intercement and Sephaku Cement) located in five provinces (Gauteng, Western Cape, North-West, KwaZulu-Natal and Eastern Cape) of South Africa. Respondents had backgrounds in cement processing/technology, production, operations, Safety, Health and Environment (SHE), Safety, Health, Environment and Quality (SHEQ) and Occupational Health and Safety (OHS). The highest qualification of most of the respondents were a university Bachelors degree, while some also had post-graduate education. Males (54.5%) and females (45.5%) were almost equally represented. Participants represented age groups 21 to 50 years of age (Table 3-2).

3.5 Data analysis

Data analysis involves studying collected data to discover information. Cohen (2007) defined it as *“organizing, accounting for, and explaining data to help interpret, communicate and structure research findings”.* The sections below describe the data analysis of experimental (laboratory data) in Section 3.5.1, and survey response data (Section 3.5.2).

3.5.1 Experimental data analysis (RO1 and RO2)

Analysis of laboratory data was conducted by way of comparing the results of the three samples with one another and with existing data (for coal and RDF), as well as minimum criteria for cement manufacturing in table format. The performance of the results was measured by comparing them with the existing accept and reject criteria of international standards and specifications of local cement kilns such as PPC and NPC.

Optimisation of carbon benefit considered the net calorific value (CV), synthetic CO_2-eq per tonne (relative to coal) and, ultimately, CO_2 saved per tonne (%) (relative to coal) of three different RDF samples. CO_2 emissions of RO2 were calculated using the method explained in Section 3.4.2.2)

3.5.2 Analysis of survey responses (RO3)

To compare the responses of respondents to the Likert-scale statements (Sections 2 to 5 of the questionnaire), a frequency table was compiled to record the number of responses falling in each interval (1 to 5, i.e., level of agreement).

Open-ended responses related to the opportunities and challenges of using MSW as RDF in cement production were thematically analysed. This was done through an intuitive process of discovering themes and categories based on responses from participants. The responses were divided into themes based on the frames mentioned. The frequency of mention of specific phrases determined the importance/ranking of an opportunity or challenge.

3.6 Ethical considerations

The researcher is familiar with the North-West University policy on research ethics and guaranteed ethical practice in the research process. Permission to carry out the research was requested from the North-West University, Faculty of Natural and Agricultural Science (FNAS) Ethics Committee (Ethics number: NWU-01231-22-A9). The researcher was enrolled in a research ethics course followed by a review in the form of a test. The committee considered the research a lower risk to human health and ethical valuations.

Furthermore, the researcher considered the potential risks associated with the data collection process. For example, through experimental research and questionnaire surveys, there is a risk of access to patented and confidential information. To alleviate such risks, the researcher offered full disclosure of the research process and findings and requested permission to publish the results.

All research participants were required to provide informed consent (see Annexure A) before commencing with the survey questionnaire.

3.7 Methodological assumptions and limitations

The methodological assumptions and limitations should be read in conjunction with the research scope, as outlined in Section 1.4 of this dissertation.

The following methodological assumptions and limitations should also be noted.

- To investigate and illustrate the development of MSW into an RDF, the research generated primary data through the experimental exercise and survey questionnaires.
- MSW was not used or tested in a cement kiln during actual cement production.

- The researcher resorted to utilising a facility that manages pre-contaminated feedstock as source of RDF, due to the unavailability (no access) to a municipality with a Material Recovery Facility that can separate waste.
- The researcher could not find affordable equipment that could measure the direct emissions of CO_2 from RDF.
- The researcher used the effective CO_2 emissions factor method to measure carbon dioxide. The assumptions related to the calculation of the effective CO_2 emissions factor for RDF are provided in Section 3.4.2.2 above. This method may not necessarily give an exact figure of carbon dioxide but rather an estimate. When carbon is emitted, it is either carbon monoxide or carbon dioxide. It becomes imperative to use testing equipment that can distinguish the two.
- The researcher acknowledges that the co-processing of RDF in thermal processes during cement manufacturing may produce emissions such as particulate matter (PM), sulphur dioxide, oxides of nitrogen, hydrogen chloride/fluoride, heavy metals, and dioxins and furans (PCDD/Fs). These emissions were not included in the scope of the research.
- Opportunities and challenges towards the use of MSW as RDF for cement manufacturing are based on perceptions of participants from the cement manufacturing industry. Perceptions may or may not be an accurate reflection of actual opportunities and challenges. The opportunities and challenges mentioned by participants were, however, also discussed against reported opportunities and challenges found in literature.

3.8 Data reliability and validation

In research, a measuring instrument can be reliable but invalid. However, if a measuring instrument is valid, it is also likely to be reliable. Thus, reliability alone is not sufficient to ensure validity (SÜRÜCÜ *et al*,.2020). That is why researchers who use logical positivism employ experimental methods and quantitative measures to test hypothetical generalisations. This scientific paradigm is based on data reliability and data validity.

Table 3-3 provides the precision criteria and standard method range for moisture-, volatile matter-, ash- and fixed carbon content analysis. The figures in Table 3.3 show the accuracy of the results. The accuracy is represented by the standard range, which is guided by the ASTM standard.

Table 3-3: Precision criteria and standard method range (ASTM D7582)

Analysis Description	Test Method	Precision Criteria SD%	Standard Method Range
Moisture %	ASTM D7582	0.69%	0.29% - 0.76%
Volatile dry basis %	ASTM D7582	1.32%	1.0% - 3.5%
Ash Dry Basis %	ASTM D7582	0.31%	0.03% -1.73%
Fixed Carbon %	ASTM D7582	-	-

3.9 Chapter summary

The chapter discussed the research design and methodology employed in the study. Aspects relating to the data sources utilized, the sampling method, and the data analysis plan employed were addressed. The following chapter, Chapter 4, will analyse and discuss the research findings.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

This research sets out to investigate the potential use of municipal solid waste (MSW) as a refuse-derived fuel (RDF) in the process of cement production.

The following research objectives were considered:

> ***Research objective 1:*** To analyse the physio-chemical properties of Refuse Derived Fuel (RDF) for the purposes of cement production.
>
> ***Research objective 2:*** To optimise the carbon benefit of RDF as a fuel in cement processing; and
>
> ***Research objective 3:*** To investigate the opportunities and challenges for using MSW as RDF in cement production.

As outlined in Chapter 3, data was collected through a combination of scientific laboratory experiments (RO1 and RO2) and a survey questionnaire completed by industry experts in the cement manufacturing sector (RO3). The sub-sections below present the results and discussion of each of the research objectives.

4.2 Results related to RO1: To analyse the physio-chemical properties of RDF for the purposes of cement production

The physical and chemical properties of three RDF samples were analysed through proximate analysis. The three samples consisted of:

- Sample 1: 60% paper; 40% plastic;
- Sample 2: 40% paper; 60% plastic; and
- Sample 3: 50% paper; 50% plastic.

The physical and chemical results are outlined in Sections 4.2.1 and 4.2.2 below. Results are compared to analysis results found in the literature (Zhang *et al.,* 2023) of coal and minimum specifications/criteria required by South African cement manufacturers (Intercement and PPC) for RDF. The research by Zhang *et al*. (2023) was considered because it used bituminous coal, which is the same coal used in the South African cement sector as highlighted by Ratshomo *et al*. (2014). The coal results are considered suitable for comparison with the three RDF samples because bituminous coal is it the same grade/type/consistency of coal. The minimum specifications/acceptance criteria for RDF for cement production were only made publicly available by two cement manufacturers, in this case, Intercement and PPC, and were therefore used for comparison.

4.2.1 Physical analysis results

Physical parameters analysed included moisture, volatile matter and ash content of the three samples (Table 4-1), according to ASTM standard D7582. These results are compared to the morphological analysis of coal by Zhang *et al,* (2023) & Nowak (2023) to establish the fitness of RDF as a capable alternative fuel in cement manufacturing. The physical composition results are also compared to the minimum specifications/criteria (accept or reject criteria) for moisture and ash content of RDF for cement manufacturing as required by Intercement and PPC in South Africa (Table 4-1). These cement manufacturers did not have listed specifications for percentage volatile matter content.

Table 4-1: Laboratory test results for the physical analysis of RDF

Physical characteristics	**Sample 1** **60% Paper, 40% Plastic**	**Sample 2** **40% Paper, 60% Plastic**	**Sample 3** **50% Paper, 50% Plastic**	**Morphological analysis of coal (Zhang *et al*. 2023)**	**Intercement criteria for RDF**	**PPC criteria for RDF**
Moisture content	3.05%	1.60%	2.24%	5.3%	<20%	<12%
Dry matter/ Volatile matter content	79.48%	87.64%	83.24%	32.9%	NA	NA
Ash content	16.26%	10.27%	13.39%	4.2 %	<20%	<15%

Table 4-2 provides the physical characteristics of RDF found in literature. The analysis was done for RDF in Pakistan where combinations of synthetic to biogenic carbon RDF ratios were 55% to 45% respectively (Azam *et al*.,2021), 55 % biogenic content in Algeria (Sakri *et al*., 2021), 50 per cent biogenic content in Kazakhstan (Kuspangaliyeva *et al*., 2021) and 55% biogenic content in Egypt (Hemidat *et al*., 2019).

Table 4-2: Physical characteristics of RDF from literature

Physical characteristics	Pakistan (Siddiqi *et al.,* 2021)	Algeria (Sakri *et al*., 2021)	Kazakhstan (Kuspangaliyeva *et al*., 2021)	Egypt (Hemidat *et al*., 2019)
Moisture content	1.8%	13.2%	1.6%	25.5%
Dry matter/ Volatile matter content	76.4%	87%	86.2%	-
Ash content	10.3%	14.03%	7.07%	18.15%
Calorific Value (MJ/kg)	22 MJ/kg	16 MJ/kg	29 MJ/kg	15.58 MJ/kg

These combinations are seen to be consistent with the moisture content as the higher the biogenic content the higher the moisture. The following subsections will discuss and compare the different RDF combinations.

4.2.1.1 Moisture content

All three of the RDF samples analysed for the purposes of this dissertation had a moisture content of less than 5%, ranging from 1.60% to 3.05% (Table 4-1). This is less than the moisture content of coal (Zhang, *et al.,* 2023) and well below the moisture content specifications of Intercement and PPC (below 20% and below 12%, respectively) (Table 4-1). All three samples are, therefore, deemed to be efficient as an RDF alternative for coal with respect to their moisture content. It must be noted that the RDF samples were subjected to a drying process (see Section 3.4.1.1.5 in Chapter 3) prior to analysis.

The literature reviewed in Chapter 2 (Section 2.7.2.1.2) showed that considering the morphology of fuels, the moisture content and the relative calorific value of the same fuel will always have an inverse relationship. This is because the higher the moisture, the lower the dry matter, which implies lesser combustible mass.

Table 4-1 shows that Sample 2 (40% paper, 60% plastic) has the least moisture content (1.60%), which supports the relationship with calorific value (CV), as the same sample has the highest CV (of 30.4 MJ/kg) as shown in Table 4-5, while Sample 1 (60% paper, 40% plastic), had the highest organic content, and thus also had the highest moisture content of 3.05%. The moisture content of the samples analysed in this research was in line with the results found Siddiqi *et al.* (2021) and Kuspangaliyeva *et al.* (2021), but significantly lower than the moisture content found by Sakri *et al*. (2021) and Hemidat *et al*. (2019) (see Table 4-2).

Sakri *et al.* (2021), supported the inverse relationship between moisture content and combustible volatile matter by pointing out that the most common alternative fuel in cement production is the end-of-life tyres, due to their lower moisture content, consistency and higher CV (of at least 35 MJ/kg).

As far as moisture content is concerned, all three of the samples are found to be suitable alternatives for coal for the purposes of cement manufacturing, with moisture content well below the 12% and 20% moisture content limits prescribed by Intercement and PPC for RDF.

4.2.1.2 Dry matter/volatile content

Dry matter is representative of the actual combustible mass from a solid fuel. Unlike moisture content, dry matter has a positive relationship with the relative calorific value (CV) of the fuel (as illustrated in Table 4-2). When a fuel has higher volatile matter, it will have lower boiling points and can be ignited at relatively low temperatures, allowing for the volatiles to be easily converted into gas (Tiburcio, 2021).

Table 4-1 shows that all three of the RDF samples analysed a higher volatile matter content than coal. Sample 2 (which has the least amount of organic matter) had the highest volatile matter content (87.64%). The volatile matter content of the three samples analysed (Table 4-1) was also in line with what other authors have found for RDF (Table 4-2). As mentioned earlier, the two cement manufacturers did not have any specifications for volatile content.

4.2.1.3 Ash content

Ash content, like moisture content, has an inverse relationship with the energy content (calorific value) and flare time of the fuel. The higher the ash content, the lesser the actual burning time. The correlation is shown by the relationship between ash content and dry matter (Table 4-2). High ash content is an undesirable characteristic of RDF. Much of the ash accumulates in the pre-calciner of the kiln and is usually incorporated into the clinker. This process needs to be monitored closely because it becomes critical to control the elements of the ash.

The ash content of the three samples analysed ranged between 10.27% and 16.26% (Table 4-1). When compared to coal (ash content of 4.2%) the RDF samples analysed for this research had a relatively high ash content (i.e., coal has better ash conversion than RDF). However, the ash content of all three samples was within the minimum criteria of Intercement (<20%) and the ash content of samples 2 and 3 were within the minimum criteria of PPC (<15%) (Table 4-1).

Furthermore, the ash content compared well to what was found for RDF reported in the literature (Table 4-2). Specifically, the RDF analysed in research done in Egypt (Hemidat *et al*., 2019) had a comparatively higher ash content (18.5%), and lowest calorific value of 15.58 MJ/kg.

4.2.2 Chemical and elemental analysis of RDF

Moisture content and ash ratio are part of the physical characteristics of RDF. It is imperative to control these characteristics because they have a significant impact on the quality of the cement. The research also included chemical analysis of the RDF, because, in the pre-calciner, the fuel comes in direct contact with the raw material. As highlighted by Khan *et al*. (2021) (see Section 2.7), excessive amounts of chemicals can compromise the clinker quality and can induce corrosion of the plant or emission of carcinogens.

Elemental parameters analysed included the hydrogen, sulphur, chlorine and nitrogen content of the three samples (Table 4-3). These elements represent the volatile matter of the RDF. Again, the laboratory results of the three samples analysed are compared to the morphological analysis of coal by (Zhang, *et al.,* 2023) to evaluate the elemental/chemical characteristics of the different RDF samples against coal, and to establish the fitness of RDF as a capable alternative fuel in cement manufacturing. The chemical composition results are also compared to the minimum specifications/criteria (accept or reject criteria) for sulphur and chlorine content of RDF for cement manufacturing as required by Intercement and PPC in South Africa (Table 4-3). These cement manufacturers do not have specifications for hydrogen and nitrogen content. Table 4-4 provides the elemental characteristics of RDF found in the literature.

Table 4-3: Laboratory test results for the elemental/chemical analysis of RDF

Chemical characteristics	**Sample 1** **60% Paper, 40% Plastic**	**Sample 2** **40% Paper, 60% Plastic**	**Sample 3** **50% Paper, 50% Plastic**	**Morphological analysis of coal** (Zhang, *et al.,* 2023)	**Intercement criteria for RDF**	**PPC criteria for RDF**
Sulphur content	0.58%	0.23%	0.15%	0.52%	3.0%	<0.5%
Chlorine content	0.17%	0.13%	0.13%	0.2%	0.3%	<0.5%
Hydrogen content	8.49%	10.56%	9.63%	3.57%	NA	NA
Nitrogen content	0.27%	0.32%	0.32%	NA	NA	NA

Table 4-4: Chemical/elemental characteristics of RDF from literature

Physical characteristics	Sakri *et al.* (2021) Algeria	Hemidat *et al.* (2019) Egypt	Sidiqqi *et al.* (2021) Pakistan	Zhang, *et al.,* (2023) China
Hydrogen content	-	0.03%	0.3%	6.8%
Sulphur content	-	0.06%	0.24%	0.06%
Chlorine content	0.58%	1.03%	0.3%	1.0%
Nitrogen	-	53%%	1.4%	1.5%

4.2.2.1 Sulphur content

The presence of sulphur in RDF is inevitable, sulphur is inevitably released in the combustion of municipal solid waste, especially plastics, organic waste, and textiles (Wang *et al*., 2021). According to research by NCRR (1980), sulphur is quite undesirable in cement production for two reasons. Firstly, the presence of sulphur may result in the formation of sulphur dioxide, which is a pollutant; and secondly, sulphur may interfere with the clinkering process in cement production. Clinker is predominantly made from the conversion of calcium carbonate into calcium oxide in the pre-calciner. Clinkering which occurs at higher temperatures can be compromised by the presence of significant amounts of sulphur, as the chemical reaction can turn the product into calcium sulphate. A high sulphur content (>0.5%) is, thus, undesirable for cement production.

The sulphur content of the three samples analysed ranged from 0.15% to 0.58%, with Sample 1 having the highest sulphur content exceeding the 0.5% threshold (Table 4-3). Samples 2 and 3, with the lower biogenic material (paper content), had relatively low sulphur concentrations and outperformed coal (which had a sulphur concentration of 0.52%)(Zhang, *et al.,* 2023) , (Nowak, 2023). Samples 2 and 3 were also within the acceptable sulphur ranges of Intercement and PPC (<0.5%). The sulphur content in the samples were comparable to what Sidiqqi *et al.* (2021) found for RDF in Pakistan.

4.2.2.2 Chlorine content

During cement manufacturing, it is imperative to keep the chlorine content of RDF lower than 0.3% to avoid its corrosive attributes in the rotary kiln (Wu *et al*., 2021). The chlorine (Cl) concentration/content of the three RDF samples was established using the ion chromatography ultimate analysis test method, as explained in Chapter 3.

The chlorine content of the three samples ranged from 0.13% to 0.17% (Table 4-3). All three samples outperformed coal (0.2% chlorine content) and fell within the acceptable chlorine ranges for RDF as proposed by Intercement (<0.3%) and PPC (<0.5%). The chlorine content of the three samples were relatively low, when compared to the chlorine levels measured in RDF by Sakri *et al.* (2021) in Algeria, Hemidat *et al.* (2019) in Egypt, Sidiqqi *et al*. (2021) in Pakistan and Wang *et al.* (2014) in China.

4.2.2.3 Hydrogen content

Hydrogen is a renewable and highly volatile element found in RDF. A higher hydrogen content in the RDF is quite desirable as it improves the calorific value (CV) and the relative ignition characteristics of RDF as a fuel.

The hydrogen content of the three samples ranged from 8.49% to 10.56%, with Sample 2 (with the higher plastic content) having the highest hydrogen content at 10.56% (Table 4-3). The hydrogen content of the three samples was relatively high when compared to that of coal (3.57%) and the hydrogen content of RDF found in the literature ranging between 0.03% and 6.8% (Table 4-4). The cement manufacturers did not have any minimum standards/acceptance criteria for hydrogen content.

The percentage difference in hydrogen found in RDF when compared to coal partially explains why RDF are considered to be more “environmentally friendly” than coal. When burned, hydrogen is transformed into water vapor (H_2O) and not carbon dioxide (CO_2). The reason for the higher hydrogen content in RDF can be ascribed to the presence of a significant amount of low-density polyethylene (LDPE) plastics. LDPE plastics are made up of hydrogen and carbon chains that are released during combustions (Hu *et al*., 2022). While it is desirable, it is imperative to be cognisant of how hydrogen reacts with the presence of chlorine in the fuel. When hydrogen reacts with a significant portion of chlorine at higher temperatures (see Section 4.2.2.2), a corrosive agent - hydrogen chloride is formed (Yu *et al*., 2021), which is undesirable.

4.2.2.4 Nitrogen content

Unlike hydrogen which is inherently in the air, nitrogen is a product of combustion. Nitrogen oxide (NO_X) is the source of acid rain and the creation of particulate matter (in the atmosphere (Siddiqi *et al.,* 2021). The nitrogen content in RDF should, therefore, be kept as low as possible.

In South Africa, the NEMAQA revised a list of activities which result in atmospheric emissions which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage (GNR. 893 of November 2013) (Molewa,2015). Subcategory 5.5 of this list provides emission limits for *Cement Production (using alternative fuels and/or resources)*. The permissible amount of oxides of nitrogen is 800 mg/kg for new installations and 1200 mg/kg for existing installations. These regulations can evolve, and it is essential to stay up to date with the latest guidelines to ensure compliance with environmental standards (Hajinezhad *et al*.2016).

The nitrogen content of the three samples analysed ranged from 0.27% to 0.32%, with Sample 1 (with higher paper and lower plastic content) having the lowest nitrogen content (Table 4-3). The nitrogen content of all experimental samples is within the permissible range in the South African new installation context, and significantly lower than the nitrogen content measured in RDF by other authors (see Table 4-4).

4.3 Results related to RO2: To optimise the carbon benefit of RDF

During the industrial revolution, the demand for cement was derived from the human need to erect structures. Historically, the cement production process was determined by operational efficiency [represented by calorific value (CV) and volatile matter] and technical efficiency (represented by moisture and chemical content) (Kuspangaliyeva *et al*., 2021). More recently, the environmental performance of fuels has also become important.

Renewable energy sources, such as RDF have been hailed to be innovative method of energy recovery. RDF has advanced the circular economy through the recovery of energy from waste and has advanced waste-to-energy in many countries around the world. To reduce the impact of CO_2 (typically related to the burning of fuels), the researcher focused on the morphology of plastic in RDF as a synthetic fossil fuel. When plastic is burned, non-renewable synthetic carbon stocks are emitted into the atmosphere. Plastics are predominantly a product of carbon and hydrogen (Hu *et al*.2022).

To optimise the carbon benefit of RDF as a fuel, a balance needs to be struck between the biogenic carbon (paper) and synthetic carbon (plastic) content of RDF. An RDF sample with a higher synthetic content (in this case, plastic) will have higher fixed carbon content, but also a higher potential for CO_2 emissions. To optimise the carbon benefit of RDF, and not compromise the natural carbon cycle, different combinations of plastic and paper were mixed to meet the international RDF standards, especially the calorific value (CV), without compromising its operational efficiency. CV was tested using ASTM D5865, while fixed carbon was tested by ASTM D7582. Fixed carbon is important because it shows how efficient a fuel is as far as calorific value goes. Based on the literature reviewed (Chapter 2), the following conclusions can be drawn to be acceptable values for fixed carbon and calorific value (CV):

- CO_2 emissions: Net zero (Carbon Tax Act, 2021)
- Net calorific value (CV): >20MJ/kg

- Fixed Carbon- as low as possible

While the CV need to be optimised, fixed carbon and CO_2 emissions need to be kept at a minimum.

Table 4-5 provides the laboratory test results of fixed carbon and calorific value, and calculated CO_2 emission factors of the three samples included in this research. The sub-sections below elaborate on these parameters.

Table 4-5: Laboratory test results of fixed carbon and calorific value

Fuel characteristics	**Sample 1** **60% Paper, 40% Plastic**	**Sample 2** **40% Paper, 60% Plastic**	**Sample 3** **50% Paper, 50% Plastic**	**Morphological analysis of coal** (Zhang, *et al.*, 2023)	**Intercement criteria for RDF**	**PPC criteria for RDF**
Fuel ratio	40% synthetic, 60% biogenic	60% synthetic, 40% biogenic	50% synthetic, 50% biogenic	100% fossil fuel	-	-
Carbon %	52.3%	61.02%	56.65%	65.5%	-	-
Fixed Carbon %	1.211%	0.4822%	1.128%	-	-	-
Net calorific value (CV) MJ/kg	27.01 MJ/kg	30.4 MJ/kg	28.15 MJ/kg	28 MJ/kg	20 MJ/kg	>21MJ/kg

4.3.1 Carbon dioxide emissions

In order to calculate CO_2 emissions for stationery combustion systems such as cement production, the researcher utilised the direct emission factor method proposed by Gillenwater (2005) and Fott *et al*. (2006) as explained in Section 3.4.2.2 of this dissertation, where $EF(CO_2) = (44/12)(C^r/Q)$ The calculated CO_2 emissions (in tonnes CO_2 per TJ) of the three RDF samples are provided in Table 4-6. For comparison, the CO_2 emissions for hard coal cited by Imran *et al.* (2014) are provided.

Table 4-6: Calculated CO_2 emissions (in CO_2-tonnes/TJ) using the carbon emissions factor equation

Fuel characteristics	Sample 1 60% Paper, 40% Plastic	Sample 2 40% Paper, 60% Plastic	Sample 3 50% Paper, 50% Plastic	Hard coal (Imran *et al*., 2014)
C^r (Carbon %)	52.3	61.02	56.65	-
Molecular weight ratio	44/12	44/12	44/12	-
Q (Net calorific value (CV) MJ/kg)	27.01	30.4	28.15	-
EF-CO_2 (tonnes/TJ)	**70.6**	**74.8**	**72.9**	**94.6**

Table 4-6 shows that Sample 1, with the higher paper content, would produce the least CO_2 emissions per weight (70.6 CO_2-tonnes/TJ). This may be attributed to a higher biogenic fraction in the sample compared to Sample 2 (which has the highest synthetic carbon), which would produce the highest CO_2 emissions (74.8 CO_2-tonnes /TJ). When compared to the EF-CO_2 of coal (Imran *et al.*, 2014), all three samples showed lower emissions factors by at least 20%.

The emitted carbon content of the three samples ranged between 52.43% and 61.02% (Table 4-6). Because of the higher plastic content of Samples 2 and 3, these samples had a higher carbon emission factor than Sample 1 (Table 4-5). The RDF samples all had a lower carbon content than coal (65.5%) (Table 4-5). (Zhang, *et al.,* 2023)

On the other hand, Sample 2 (with the highest plastic content) has the least fixed carbon (0.4822%). Fixed carbon is a residue of anaerobic combustion. The amount of fixed carbon in a fuel reflects the efficiency of its inherent energy production and combustion properties (Islam *et al.*, 2019). The lower the fixed carbon, the higher the CV of the fuel (Table 4-5). The cement manufacturers do not have minimum criteria for carbon, but they do have minimum criteria for CV (Table 4-5). CV is further discussed in Section 4.3.3 below.

4.3.2 Carbon dioxide emission reaction

The experiment was done under excess air conditions. The equations below show how the carbon gases released from the combustion reaction are go through complete combustion. The complete combustion of carbon means that of the carbon would be turned into CO2 (Giugliano et al., 2016). Hence the three samples in the experiment are predominantly carbon dioxide. Carbon dioxide is formed when a carbon molecule and an oxygen molecule react . However, when half oxygen or no oxygen molecules are present, the reaction generates carbon monoxide.

Complete combustion: $1\ Carbon\ + 1\ Oxygen\ = 1\ CO2$ (Carbon dioxide)

Incomplete combustion: $1\ Carbon + 0.5\ Oxygen = 1\ CO$ (Carbon monoxide)

The reason why cement factories are high CO2 emitters are because carbon combustion takes place in open air. However, it is not always the case. Some degree of incomplete combustion happens (Gairola & Bhatt, 2021), Carbon monoxide, volatile organic compounds, organic compounds are also formed and significantly affect the surrounding environment in the process.

4.3.3 Calorific value (CV)

The calorific value (CV) of a fuel is mainly determined by its physical morphology. For instance, bituminous coal is more popular in rotary kilns because it has a lower moisture content, and higher CV due to its hydrophobic nature (Zhong *et al.*, 2018). As mentioned in Section 4.2.1.3, the ash content of the fuel is important as it is linked to the CV of the fuel, and determines the amount of residue that will be generated after the combustion process (Azam *et al.,* 2019).

A CV of at least 20 MJ/kg is ideal for cement manufacturing. Scarlet *et al.*, (2015) highlighted that untreated South African MSW has a high moisture and is unsuitable for use as RDF, while Kaza *et al.*, (2010) emphasised that RDF should have an uncompromised CV of at least 18 MJ/kg to be technically efficient (also see: Section 2.7.2.1.1).

The calorific value (CV) of the three samples was tested using the bomb calorimeter test (ASTM D5865 11a), which dries the samples in open air and furnaces periodically. The CV of the three samples analysed ranged from 27.01 MJ/kg to 30.4 MJ/kg (Table 4-6), which compared well with the CV of coal (28 MJ/kg) (Table 4-5). Sample 2, with the highest plastic content, had the highest CV (30.4 MJ/kg) and the lowest ash content (see Table 4-1). Fixed carbon is also the lowest in Sample 2 and highest in Sample 1 [with the highest biogenic (paper) and lowest synthetic (plastic) carbon content] (Table 4-5).

All three of the RDF samples had a favourable CV for cement production when compared to the acceptance criteria of Intercement (20 MJ/kg) and PPC (>21 MJ/kg) (Table 4-5).

4.3.4 Biogenic versus synthetic carbon and CO_2 emissions

As mentioned earlier, the co-processing of RDF in thermal processes during cement manufacturing may produce other emissions such as particulate matter (PM), sulphur dioxide, oxides of nitrogen, hydrogen chloride/fluoride, heavy metals, and dioxins and furans (These emissions were not included in the scope of the research. As part of the second research objective of this study, CO_2 emissions are calculated. In Section 1.2, it has been highlighted that at least 5% of the global greenhouse gas emissions come from cement production. Specifically, approximately 500 to 900 kilograms of CO_2 equivalents are emitted for every tonne of cement produced with coal (Mahasenan *et al.,*2003), (2016; Rychter *et al*., 2021). Research by Sakri *et al.* (2021) and Hemidat *et al.* (2019) suggested that replacing coal in cement production with at least 15% RDF can result in a 70% reduction of CO_2 equivalents.

Research by Durak (2023) asserted that what often gets overlooked is that conventional plastic is made from fossil fuels and is a product of the oil and gas industry. This school of thought was pursued by the researcher to explore the possibilities of reducing the synthetic carbon emissions from plastic (only) by substituting it with more biogenic carbon (in the case of this research, paper). Furthermore, utilising RDF reduces the need to mine for coal and reduces waste to landfill. Mining coal introduces new carbon stocks both from methane gas release from coal traps and the loss of land cover plants (Kartisaria *et al.*, 2019), while the reduction of waste to landfill may reduce methane and CO_2 from waste disposal processes.

The research findings acknowledge that carbon is the foundation of all life on earth, and the source of all the energy consumed by human civilisation (Riebeek, 2011). Civilisation cannot do away with carbon. In cement production, biogenic carbon (such as paper) can be prioritised over synthetic carbon (such as plastic) in order to reduce potential CO_2 emissions, while still achieving the same fuel-based outcomes (CV, fixed carbon, etc.) in cement manufacturing.

4.3.5 Summary: RDF as an alternative to coal

Table 4-7 below provides the technical, operational, and environmental efficiency of the three RDF test samples. These properties are relevant when considering the substitution or co-processing of RDF with coal for cement manufacturing.

Table 4-7: Suitability of the three RDF samples tested as an RDF to substitute/ replace coal in cement manufacturing

Minimum criteria/specifications	**Sample 1** **60% Paper, 40% Plastic**	**Sample 2** **40% Paper, 60% Plastic**	**Sample 3** **50% Paper, 50% Plastic**
Operational efficiency			
Calorific value (CV) (>21 MJ/kg)	27.01 MJ/kg	30.4 MJ/kg	28.15 MJ/kg
Ash content % (<15%*) *Value specified by PPC; Intercement: <20%	16.26% *In line with Intercement specs/ exceeds PPC specs	10.27%	13.39%
Volatile matter % (no range specified)	79.48%	87.64%	83.24%
Fixed carbon content %	52.3%	61.02%	56.65%
Technical efficiency			
Moisture content % (<12%*) *Value specified by PPC, Intercement: <20%	3.05%	1.60%	2.24%
Sulphur content % (<0.5%)	0.58%	0.23%	0.15%
Chlorine content % (0.3%*) *Value specified by Intercement, PPC: <0.5%	0.17%	0.13%	0.13%
Environmental efficiency			
EF-CO_2 (tonnes/TJ)	**70.6**	**74.8**	**72.9**

Summarising the findings presented in Table 4-7, the following observations are made:

- **Operational efficiency**: While Sample 2 has a more favourable CV (30.4 MJ/kg) and lower ash content (10.27%), it has the highest volatile matter content (87.64%). Sample 3 on the other hand, have a lower volatile matter (83.24%) and also meets operational specifications for CV and ash content. Sample 1 was considered to be unsuitable, because it exceeded the ash content specifications of 15%. It also had the lowest CV of the three samples.

- **Technical efficiency**: As far as technical efficiency is concerned, both Samples 2 and 3 were considered to be suitable alternatives to coal in cement production. While Sample 2 had the lowest moisture content (1.60%), Sample 3 had a lower sulphur content. The chlorine content of Samples 2 and 3 were equal. Again, Sample1 was considered to be unsuitable, because the sulphur content (0.58%) was higher than the proposed 0.5% level.
- **Environmental efficiency**: For this research, environmental efficiency only considered CO_2 emissions. Sample 1, with the highest paper-to-plastic ratio (60:40) had the lowest calculated EF-CO_2 (70.6 tonnes/TJ), while Sample 2 with the lowest paper-to-plastic ratio (40:60) had the highest EF-CO_2 (74.8 tonnes/TJ). All of the samples, however, had lower calculated CO_2 emissions than coal (94.6 tonnes/TJ) (Imran *et al*., 2014).

When considering the physical-chemical characteristics in the context of operational, technical and environmental efficiency, both Sample 2 (40% paper, 60% plastic) and Sample 3 (50% paper, 50% plastic) were suitable alternatives for coal in cement manufacturing.

4.4 Results related to RO3: Opportunities and challenges for RDF in cement production

This section presents the findings as gathered from survey questionnaires completed by cement manufacturing industry experts. It investigates the (perceived) challenges and opportunities industry experts are facing in incorporating RDF as a fuel in cement manufacturing.

As explained in Section 3.4.3.2, statements related to the technical/operational-, legal- (policy and licencing), environmental- and economic implications of using RDF as a fuel (mostly gleaned from literature) were ranked using a 5-point Likert scale (where 1 = strongly disagree and 5 = strongly agree). The responses from twenty-two (22) industry expert respondents are indicated in Table 4-8, which is presented as a frequency table (i.e. percentage responses per Likert-scale category). As indicated earlier, in Section 3.4.3.2.5, industry experts represented five different cement manufacturing companies located in six different provinces of South Africa.

Table 4-8 provides the mean (average) Likert score per question (where a mean Likert score below 3 indicates disagreement with the statement and a Likert score above 3 indicates agreement with the statement). All statements were phrased positively, in favour of using MSW as RDF for cement production (i.e. *“RDF can technically replace coal in cement manufacturing”* or *“The South African policy context is supportive towards the use of RDF in cement manufacturing”*) to allow for comparison between the different statements. This means that statements related to using coal for cement production (as opposed to RDF) were stated in a “negative” manner.

The main findings related to Table 4-8 are discussed in the sub-sections below.

Table 4-8: Responses from cement manufacturing industry experts (n = 22) regarding the potential to use MSW as RDF as a fuel in cement production

Statements	**Frequency of Likert scale responses (% of responses)**					
	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**	**Mean**
Section 1: Information about respondents (not included here – refer to Section 3.4.3.2.5)						
Section 2 Technology/Operational questions						
2.1 My cement manufacturing plant is compatible with the dry cement production process (Karstensen, 2007).	0	0	9%	0	91%	4.8
2.2 Our cement kiln has a fuel feed system for the pre-calciner (Hemidat *et al.,*2019).	9%	0	41%	9%	41%	3.7
2.3a I am familiar with using alternative fuels (AF) in cement production (Kara *et al*., 2011).	0	0	4.5%	4.5%	91%	4.9
2.3b I am familiar with refuse-derived fuel (RDF) made from municipal solid waste in cement production (Kara *et al*., 2011).	0	0	4.5%	23%	72.5%	4.7
2.4 Our company has conducted alternative fuel co-processing feasibility studies before (Oliveira, 2016).	0	0	9%	14%	77%	4.7
2.5 We have attempted using Refuse Derived Fuel (RDF) for cement manufacturing before (Oliveira, 2016).	9%	4.5%	32%	9%	45.5%	3.8
2.6 We are currently using at least one alternative fuel (AF) at our cement kiln (Kara *et al*., 2011).	0	4.5%	4.5%	14%	77%	4.6
2.7 Refuse Derived Fuel (RDF) can technically replace coal for cement kiln heating requirements (Kara *et al*., 2011).	0	4.5%	27%	23%	45.5%	4.1

Statements	**Frequency of Likert scale responses (% of responses)**					
	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**	**Mean**
2.8 To use Refuse Derived Fuels, cement kilns require advanced emissions control technology investment to be compatible with RDF (Karstensen, 2007).	0	0	27%	14%	59%	4.3
Section 3: Policy and licencing questions						
3.1 I am familiar with the *National Policy on the thermal treatment of general and hazardous waste* (GN 777 of July 2009) which allows for the coprocessing of waste as alternative fuel for cement manufacturing (GN. 777 of July 2009).	0	0	14%	27%	59%	4.5
3.2 I am familiar with *the List of activities requiring an atmospheric emissions licence* (GNR. 893 of November 2013); and sub-category 1.6, requiring the licencing of waste co-feeding combustion installations (GNR. 893 of November 2013).	0	0	9%	18%	73%	4.6
3.3 The South African policy framework is supportive of alternative fuel usage (such as the use of RDF) for cement manufacturing (GN. 777 of July 2009).	4.5%	9%	18%	27%	41%	3.9
3.4 The South African government provides sufficient support to cement manufacturers who are interested in using Refuse Derived Fuel in cement manufacturing (GN. 777 of July 2009).	9%	23%	45.5%	9%	14%	3.0
3.5 The authorisation and licencing processes to use Refuse Derived Fuel in cement manufacturing are easy and efficient (GN. 777 of July 2009).	9%	32%	41%	18%	0	2.7

Statements	Frequency of Likert scale responses (% of responses)					
	Strongly disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly agree (5)	Mean
3.6 The government sufficiently encourages interactions between municipalities and cement manufacturers by enabling public-private partnerships (Khan *et al,* 2022).	32%	36%	14%	18%	0	2.2
Section 4: Environmental questions						
4.1 Cement kilns in South Africa have some of the best emissions control in the world (Karstensen, 2007).	0	9%	36%	36%	18%	3.6
4.2 Refuse Derived Fuel (RDF) emits fewer greenhouse gases than coal (Reza *et al*., 2013).	0	4.5%	18%	32%	45.5%	4.2
4.3 Refuse Derived Fuel (RDF) emits fewer harmful emissions (PM_{10}, SO_2, etc.) gases than coal (Nutongkaew *et al.,* 2014).	0	4.5%	23%	27%	45.5%	4.1
4.4a Refuse Derived Fuel (RDF) should be considered as an alternative to coal in cement manufacturing (Nutongkaew *et al.,* 2014).	0	0	0	23%	77%	4.8
4.4b At our cement manufacturing plant, we currently have arrangements in place to use less coal.	4.5%	4.5%	4.5%	4.5%	82%	4.5
4.5 Co-processing of RDF with coal to heat up the kiln is more energy efficient (than using coal only).	9%	4.5%	36%	18%	32%	3.6
4.6 Co-processing of RDF with coal to heat up the kiln is more environmentally friendly (than using coal only).	0	9%	14%	23%	54%	4.2
4.7 Using Refuse Derived Fuel (RDF) as an alternative fuel for cement production is less harmful to the environment than landfilling of waste (Wojtacha-Rychter *et al*., 2021).	0	0	9%	4.5%	86%	4.8

Statements	**Frequency of Likert scale responses (% of responses)**					
	Strongly disagree (1)	**Disagree (2)**	**Neutral (3)**	**Agree (4)**	**Strongly agree (5)**	**Mean**
Section 5: Economic questions						
5.1 The current pricing of coal is not sustainable for South African cement manufacturers (Hemidat *et al*., 2019).	4.5%	9%	0	9%	77%	4.5
5.2 The transportation of distances and related costs of coal make it economically unfeasible as a fuel for cement manufacturers (Ratshomo *et al*., 2014).	0	4.5%	9%	18%	68%	4.5
5.3 The current pricing of coal makes alternative fuels (AF) such as RDF more economically feasible for cement manufacturing (Kara *et al*., 2011; (Hemidat *et al*., 2019).	4.5%	4.5%	14%	27%	50%	4.1
5.4 Replacing coal with alternatives would reduce our company's carbon taxes (Kara *et al*., 2011).	4.5%	4.5%	0	23%	68%	4.5
5.5 Considering the overall cost of cement manufacturing, Refuse Derived Fuel (RDF) is less expensive than coal (Kara *et al*., 2011).	4.5%	9%	32%	14%	41%	3.8
5.6 South African cement kilns can afford the infrastructure necessary to incorporate Refuse Derived Fuel (Karstensen, 2007).	9%	18%	32%	23%	18%	3.2

4.4.1 Technology/operational considerations regarding the use of RDF in cement production

When reflecting on the responses (level of agreement) related to the technology/operational considerations for using RDF in cement production (Statement 2.1 to 2.8 in Table 4-8), most respondents agreed or strongly agreed that RDF is a suitable alternative to coal for cement production (mean ranging from 3.7 to 4.9) (Table 4-8).

The majority of cement manufacturers (S2.1: 91%; Table 4-8) are using the dry process of cement production since the dry manufacturing process is generally more energy efficient compared to the wet manufacturing process. To incorporate RDF, cement kilns require a pneumatic feed system (Hemidat *et al.,*2019). The responses related to Statement 2.2. indicated that 50% of participants had cement kilns with the requisite pre-calciner fuel feeding systems (41% of respondents reacted neutral to this statement, which begs the question of whether the statement was understood or whether respondents were unsure about their fuel feeding systems) (Table 4-8). These findings do not present an overwhelming notion that feed systems are already installed and being used for RDF.

All of the respondents indicated that they were familiar with the use of alternative fuels (AF) in cement production (S2.3: 91% strongly agreed, 4.5% agreed and 4.5% neutral), while they all also indicated that they were familiar with RDF made from municipal solid waste (MSW) for cement production (S2.4: 72.5% strongly agreed, 23% agreed and 4.5% neutral). This may be a result of the fact that most of these cement manufacturers had previously educated their staff or because they have conducted a feasibility study on the use of RDF in cement production (refer to Question 2.4) (Table 4-8).

The majority of respondents (68%) agreed that RDF could replace coal for cement kiln heating requirements (S2.7), but 73% of respondents also believed that using RDF, in cement kilns would require advanced emissions control technologies (S2.8). These findings are consistent with the findings of the NCRR (1980), which stated that because RDF has a different physiology to coal, cement kiln modifications are required to accommodate the use of RDF (also see: Section 2.7.1).

When reflecting on the responses to Statement 2.5, approximately 55% of respondents agreed or strongly agreed that their company have attempted the use of RDF for cement production, while 32% of respondents were neutral, and approximately 14% disagreed or strongly disagreed. This suggests that while the majority of cement manufacturers know about RDF and believe it may be a suitable alternative to coal, not all of them have attempted to utilise RDF for cement manufacturing. However, in responses to Statement 2.6, more than 90% of respondents agreed or strongly agreed that their company are currently using alternatives to coal (other than municipal solid waste) (Table 4-8). These options may include sludge or end-of-life (waste) tyres as alternative fuels typically used in South Africa. Tyres are supplied free of charge by the Waste Bureau as part of the Industrial Waste Management Plan Scheme (Creecy, 2021). Alternative fuels other than MSW were not explored in this research.

4.4.2 Legal (policy and licencing) considerations regarding the use of RDF in cement production

The *South African National Policy on Thermal Treatment of General and Hazardous Waste* (GN. 777 of July 2009) allows for the co-processing of alternative fuels and raw materials (AFRs), which includes RDF, in cement production, while the *list of activities requiring an atmospheric emissions licence* (Molewa, 2015), requires the licencing of waste co-feeding combustion installations (subcategory 1.6) and cement production using alternative fuels and/or resources (subcategory 5.5). Statements 3.1 to 3.6 considered participants responses to the legal and policy contexts applicable to using MSW as RDF in cement production (Table 4-8).

The responses to Statements 3.1 and 3.2 indicated that all of the respondents believed that they were familiar with these legislative requirements (Table 4-8). Approximately 68% of respondents agreed or strongly agreed that the South African policy framework is supportive of alternative fuel usage (such as RDF) in cement manufacturing (S3.3). Only approximately 15% of respondents disagreed or strongly disagreed with this statement (Table 4-8). However, when reflecting on the responses to Statement 3.4, a different picture emerges. Only 23% of respondents agreed or strongly agreed that the South African government provides sufficient support to cement manufacturers interested in using RDF in cement manufacturing, while 45.5% of respondents reacted neutral and 32% disagreed or strongly disagreed (Table 4-8). Similarly, the majority of respondents (41%) felt that the authorisation and licencing processes to use RDF in cement manufacturing processes (S3.5) are difficult and inefficient (i.e. disagreed or strongly disagreed that it was easy or efficient). Forty-one percent (41%) of respondents reacted neutral to Statement 3.5, while only 18% agreed that the authorisation processes as easy and efficient (Table 4-8). These statements concur with research findings of Retief & Chabalala (2009), which report that environmental authorisation processes in South Africa are generally cumbersome and regarded as inefficient. The majority of respondents (68%) also believed that the government does not sufficiently encourage interaction between municipalities and cement manufacturers by enabling public-private partnerships (Statement 3.6) (Table 4-8). These results show that more effort is necessary in promoting partnerships between the private and the public sector to enhance the use of waste as a resource, as suggested by Ndlovu (2022).

4.4.3 Environmental considerations regarding the use of RDF in cement production

As mentioned earlier, it is no longer only the technical and operational considerations that need to be taken into consideration when considering the use of RDF as a fuel in cement production, environmental considerations are equally important. Statements 4.1 to 4.7 aimed to gather participants' perceptions on the environmental considerations of using MSW as RDF in cement production (Table 4-8).

Due to the heterogeneous nature of municipal solid waste (MSW), it is imperative to evaluate the possible emissions resulting from its combustion. The fuel drying process of the rotary kiln requires highly combustible fuel to facilitate calcination as it requires at least 17 MJ/kg to reach the minimum temperature of 1400° C (Wojtacha-Rychter *et al*., 2021). These processes may result in emissions and emissions control technologies are, therefore, necessary.

Statement 4.1 aimed to determine respondents' perceptions of the emissions control of cement kilns in South Africa. While 54% of respondents agreed or strongly agreed that South African cement kilns have some of the best emissions control in the world, 36% of respondents reacted neutral to this statement, and 9% disagreed (Table 4-8). The majority of respondents (approximately 77%) agreed or strongly agreed that RDF emits fewer greenhouse gases than coal (S4.2) (Table 4-8). Similarly, 72% of respondents agreed or strongly agreed that RDF emits fewer harmful emissions than coal (S4.3) (Table 4-8). All of the respondents agreed (23%) or strongly agreed (77%) that RDF should be considered as an alternative to coal in cement manufacturing (S4.4a). Moreover, approximately 86% of respondents agreed or strongly agreed that they currently have arrangements in place to use less coal at their cement manufacturing plant (S4.4b) (Table 4-8). These responses indicate the cement manufacturers' intent to use less coal and indicate that RDF is considered an alternative, which may be more environmentally sustainable.

Responses to Statement 4.5, however, show a divide on whether RDF is more operationally competent as much as coal. When confronted with the statement *"Co-processing of RDF with coal to heat up the kiln is more energy efficient (than using coal only)"*, 50% of respondents agreed or strongly agreed with the statement, while 36% of the respondents felt neutral and almost 15% disagreed or strongly disagreed (Table 4-8). This concern is shared by some authors in literature. For instance, Herrero & Vilella (2018) doubt the fitness of RDF as a fuel as their research pointed out how MSW can be toxic since most kilns do not monitor the emissions of the fuel on the assumption that RDF is "environmentally friendly". However, findings by Siddiqi *et al*., (2021), Sakri *et al.,* (2021), Kuspangaliyeva *et al*., (2021) and Hemidat *et al*., (2019) support the use of RDF in terms of its energy efficiency and environmental performance. Utilising coal (only) in cement production is argued to have more negative outcomes (than substituting or co-processing with RDF) due to the high inherent mineral content of coal that results in air pollution, with emissions of particulate matter, carbon dioxide, sulphur dioxide and oxides of nitrogen (Iacovidou *et al*., 2018). Besides negative environmental contributions, most of the remaining coal stocks in South Africa are of low quality and require to be beneficiated before they can be used locally (Isaac *et al*., 2022)

Responses to Statement 4.6 leave no doubt about the perceived environmental benefits of using coal, with 77% of respondents agreeing or strongly agreeing that co-processing of RDF with coal is more “environmentally friendly” than using coal only (Table 4-8). Lastly, most respondents strongly agreed (86%) or agreed (4.5%) that the use of RDF in cement production is less harmful to the environment than landfilling (S4.7). Arguments that discourage the use of RDF as a fuel, need to factor in the reality that landfilling MSW produces methane, which is more harmful than CO_2 or carbon monoxide. In their study, Houghton (2003) supported that the comparative impact of methane on climate change is more than 25 times greater than carbon dioxide over 100 years.

These responses indicate the perceived environmental benefits of landfill diversion of MSW in pursuit of the waste management hierarchy, while also mitigating some of the environmental impacts typically associated with cement production (using coal).

4.4.4 Economic considerations regarding the use of RDF in cement production

The last set of statements explored the perceptions of cement manufacturers with respect to the economic considerations regarding the use of RDF in cement production (Statements 5.1 to 5.6 in Table 4-8).

Substituting coal with RDF is perceived to have long-term environmental and cost benefits in cement production. Nahman (2011) argues that the cost of waste management is not always concrete or quantifiable, economically, but can be in the form of negative externalities of emissions that have a detrimental effect on the environment. This notion was also highlighted by Andrew & Rodgers, (2018) who noted the changes in emissions of CO_2 from cement production from the year 2000 at around 800 tonnes to recently around 2,2 billion tonnes in 2016 (also refer to Section 2.7.1). This change shows a classic example of the negative externalities of cement production which resulted in cement production releasing an estimated 8% of the global CO_2 emissions.

Responses to Statements 5.1 and 5.2 indicate that the cost of coal is a limiting factor for cement manufacturers. Approximately 86% of respondents agreed or strongly agreed that the current pricing of coal is not sustainable for South African cement manufacturers (S5.1), while another 86% of respondents agreed or strongly agreed that the transportation distances and related costs of coal make it economically unfeasible as fuel for cement manufacturers (S5.2) (Table 4-8). Furthermore, responses to Statements 5.3 and 5.4 support the notion that RDF is less expensive than coal and can save significantly in the carbon credits market. Seventy-seven percent (77%) of respondents agreed or strongly agreed that the current pricing of coal makes alternative fuels (such as RDF) more economically feasible for cement production (S5.3), while 91% of respondents believed that replacing coal with alternatives would reduce their company's carbon taxes (S5.4) (Table 4-8). According to the International Monetary Fund (Black *et al.,* 2023), the South African carbon tax will cost the industry R122.00 per tonne. This implies that a typical cement factory that uses at least 50 tonnes of coal per hour will owe over R6 000 in tax per hour.

Responses to Statement 5.5 (Table 4-8) show that regardless of such costs, some industry professionals in South Africa are still divided on whether RDF is less expensive than coal (55% of respondents agreed or strongly agreed, 32% of respondents neutral, and 14.5% of respondents disagree or strongly disagree). Lastly, the responses to Statement 5.6 further reflect the doubts on the affordability of the local kilns in making the necessary infrastructure adjustment to accommodate alternative fuels such as RDF, with only 41% of respondents agreeing that South African cement kilns can afford the infrastructure necessary to incorporate RDF (Table 4-8). Paszkowski (2020) argues that the use of RDF and landfill diversion has social benefits that cannot be quantified in terms of its financial contribution. The cost of RDF-supportive infrastructure such as storage units and feed systems also need to be considered in the context of the cost of landfilling.

In summary, when reflecting on the overall responses from the 22 cement manufacturers, it is perceived that RDF is an appropriate alternative to coal for cement manufacturing purposes, especially from an operational, environmental and economic perspective. While the necessary legal (policy and authorisation) framework exists for the use of RDF in cement production, respondents, however, believe that more can be done to make the authorisation processes easier and more efficient. The respondents also believe that the government can do more to encourage the use of MSW as RDF in cement production.

4.4.5 Perceived opportunities and challenges related to the use of MSW as RDF in cement production

To explore the opportunities and challenges related to the use of MSW as RDF in cement production, the last part of the survey employed two open-ended questions:

- ***Q 6.1****: I foresee the following* ***opportunities*** *for the use of Refuse Derived Fuel in cement manufacturing in South Africa; and*
- ***Q 6.2:*** *I foresee the following* ***challenges*** *for the use of Refuse Derived Fuel in cement manufacturing in South Africa.*

The aim of the open-ended questions in the survey was to employ a holistic approach in identifying the potential technical, economic, environmental, and legislative opportunities and challenges the industry faced in the effort to incorporate RDF in their fuel mix. Based on the intuitive analysis and categorisation of the responses, both opportunities (Table 4-9; Section 4.4.5.1) and challenges (Table 4-10; Section 4.4.5.2) were identified. It should be noted that these opportunities and challenges are "perceived" based on the experience, knowledge and opinions of research participants, and may or may not be realised within the South African context.

4.4.5.1 Perceived opportunities related to the use of MSW as RDF in cement production

Table 4-9 provides a summary of the perceived opportunities related to the use of MSW as RDF in cement production shown as a frequency table. Three categories of opportunities emerged from the analysis of the open-ended responses (i) technical opportunities, (ii) financial/economic opportunities and (iii) environmental opportunities.

Table 4-9: **Opportunities identified by cement manufacturing industry experts (n = 22) regarding the potential to use MSW as RDF as a fuel in cement production**

Theme	Examples of phrases mentioned	Frequency	
		n	%
Technical opportunities			
Increased kiln efficiency	“Increased volatile matter’’, “increased efficiency”, “more efficient”, “higher CV”, “improved cement manufacturing”, “better heating”	10	45%
Improved innovation	“encourages innovation”, “innovation benefits for cement manufacturers’’, “think innovatively in solving waste problems”, “waste-to-energy”	6	27%
Financial/economic opportunities			
Reduced cost of cement production	“Reduced carbon footprint”, “less carbon tax”, “cheaper than coal”, “cost effective”, “reduced cost of production’’	13	59%
Reduced cost of waste management	“landfill diversion”, “reduction in waste management cost”, “less money spent on landfill management”, “waste as a resource”	12	54%
Environmental opportunities			
Reduced greenhouse gas emissions	“less CO_2 emissions”, “reduced emissions”, “reduced carbon footprint”, “less harmful emissions”, “lowered GHG emissions”	17	77 %
Promotes landfill diversion	“landfill diversion”, “away from landfill”, “waste-to-energy”, “waste management hierarchy”, “general duty in respect of waste management”, “energy recovery from waste”	14	64%
Promotes environmental sustainability	“environmental benefits”, “environmentally friendly”, “environmental sustainability”	9	41%
Reduced fossil fuel dependency	“Coal reduction”, “energy mix”, “reduced fossil fuel dependency”, “alternatives”, “reduction of virgin resource use”	9	41%
Pollution prevention	“pollution prevention”, “MSW will not contaminate land”, “reduced air pollution”, “reduction of pollution”	7	32%
A positive change in the public perception of waste	“Climate change perception”, “waste-to-energy”, “waste as a resource”, “public perceptions”	5	23%

4.4.5.1.1 Perceived technical opportunities

One of the highlighted technical opportunities of utilising RDF in cement production, mentioned by ten of the participants (Table 4-9) is increased kiln efficiency. Respondents noted that RDF usage may lead to “increased volatile matter’’, “increased efficiency”, “more efficient”, “higher CV”, “improved cement manufacturing”, and “better heating”. As discussed in Section 4.2.1.2, high volatile matter content is a characteristic of a fuel that reflects its combustion ability. Güereca *et al.* (2015) supported the same contributions of volatile matter in RDF by indicating the cement production process inherently needs fuel with a high heat of combustion. Güereca *et al.* (2015) furthermore supported the notion that MSW has a high CV and is desirable as RDF for thermal processes in the cement industry.

Six of the 22 respondents indicated that utilisation of RDF provides for innovation and partnerships in waste management. One of the participants specifically mentioned that *“The use of RDF in cement production provides an opportunity to think innovatively about solving our country's municipal waste problems”.* Another respondent mentioned that *“MSW usage allows for the participation of different sectors when solving our municipal waste issues”*. This response is supported by the South African integrated waste management planning process, which promotes multi-sectoral awareness and contribution to the process of municipal waste management.

4.4.5.1.2 Perceived financial/economic opportunities

Respondents identified two main financial opportunities related to the use of MSW as RDF in cement production – (1) reduced cost of cement production, and (2) reduced cost of waste management. Approximately 59% of respondents believed that the use of RDF in cement production could lead to cost reduction in cement production due to “less carbon tax”, “RDF being cheaper than coal”, “RDF being cost-effective”, and “RDF leading to reduced cost of production’’. According to the South African Carbon Tax Bill, RDF can reduce the amount to be paid in carbon taxes. The cost difference between the use of coal and the use of RDF remains to be quantified in South Africa. Research by Hemidat *et al*. (2019) in Jordan, estimates that the use of RDF (instead of coal) can bring about a price reduction of as much as $489 (US dollars) per hour.

Responses from 54% of the participants suggested that utilising RDF in cement production may reduce the cost of solid waste management. In their responses, they referred to “reduction in waste management cost”, “less money spent on landfill management”, and “waste being used as a resource will cost less for disposal”. These findings are supported by Nahman (2011) and Godfrey (2017) who have both indicated that the cost of landfilling in South Africa is estimated at

R111 per tonne. Nahman (2011) highlighted the negative externalities of landfills which are typically not quantified as concrete costs. Through landfilling, societies face environmental costs such as pollution and social costs such as carcinogens that may be detrimental to health.

4.4.5.1.3 Perceived environmental opportunities

Environmental opportunities were the most frequently mentioned opportunities related to the use of MSW as RDF in cement production. Respondents mentioned opportunities related to (1) reduced greenhouse gas emissions; (2) promotion of landfill diversion; (3) promotion of environmental sustainability; (4) reduced fossil fuel dependency, (5) pollution prevention; and (6) a positive change in the public perception of waste (Table 4-9).

Concerns about the ongoing environmental degradation and finite natural resources necessitate the switch to cleaner sources of energy across all industries. Utilising RDF as a fuel reduces the impact of fossil-generated CO_2 and replaces the process with biogenic carbon that can be incorporated into the natural carbon cycle. Approximately 77% of participants mentioned that reduced greenhouse gas emissions are an opportunity related to the use of RDF in cement production. Participants mentioned “less CO_2 emissions”, “reduced emissions”, “reduced carbon footprint”, “less harmful emissions”, and “lowered GHG emissions” as opportunities (Table 4-9). This is an acknowledged advantage of AFs as highlighted by Houghton (2003) and Riebeck (2011).

Landfill diversion of waste was the second most frequently mentioned (64%) environmental opportunity related to RDF usage. Participants mentioned that RDF usage will lead to “landfill diversion” through “waste-to-energy” or “energy recovery from waste (Table 4-9). This gives effect to the “general duty in respect of waste management”, which is outlined in Section 16 of the NEMWA, which promotes the implementation of the “waste management hierarchy” (Table 4-9). The South African State of Waste Report 2018 reports that the use of MSW as RDF in cement production may divert up to 4.8 million tonnes of MSW from landfill per year, which would otherwise be landfilled.

Other environmental opportunities included the promotion of “environmental sustainability” (mentioned by 41% of respondents), the reduction of fossil fuel dependency (also mentioned by 41% of respondents) and pollution prevention (mentioned by 39% of respondents) (Table 4-9). These holistic opportunities promoting the non-conventional use of RDF promote innovation (Genon *et al*., 2008).

Lastly, five of the participants (23%) mentioned that the beneficial use of MSW as RDF may lead to a positive change in the public perception of waste (Table 4-9). One of the participants mentioned that: *“The beneficial use of waste as RDF in cement manufacturing may create awareness amongst South African citizens about the beneficial use of waste, which may cause a knock-on effect, which may cause more positive attitudes towards waste in the country”.*

The next section, Section 4.4.5.2, outlines the perceived challenges related to the use of MSW as RDF in cement production.

4.4.5.2 Perceived challenges related to the use of MSW as RDF in cement production

Table 4-10 provides a summary of the perceived challenges related to the use of MSW as RDF in cement production shown as a frequency table (n = 22). Four categories of challenges emerged from the analysis of the open-ended responses: (i) technical challenges, (ii) financial/economic challenges, (iii) environmental challenges and (iv) policy/licencing challenges.

Table 4-10: Challenges identified by cement manufacturing industry experts (n = 22) regarding the potential to use MSW as RDF as a fuel in cement production

Theme	**Examples of phrases mentioned**	**Frequency**	
		n	**%**
Technical challenges			
Meeting quality specifications	“poor quality”, “meeting specifications”, “technical specifications of cement insufficient”, “not meeting chemical standards”, “inconsistent calorific value”, “unknown fuel elements”, “high chlorine”	12	55%
Monitoring requirements	“emissions monitoring”, “additional monitoring”, “dioxins”, “unknown emissions”	9	41%
Incompatibility of cement kilns	“burner capacity”, “feeding capacity”, “infrastructure requirements”, “cement kilns not currently capable of feeding RDF”	5	23%
Financial/economic challenges			
Cost of infrastructure	“pneumatic fuel feed systems are expensive’’, “cost of infrastructure such as RDF storage and feed systems’’	16	73%
Cost of waste (once it has value)	“cost model of waste (once waste has beneficial value”	4	18%
Environmental challenges			

Theme	Examples of phrases mentioned	Frequency	
		n	%
Emissions from burning of MSW	“plastic burning”, “release of toxic emissions”, “dioxins and furans”, “organic pollutants”, “carcinogens”	7	32%
Policy and licensing challenges			
Difficulties in licensing	“unsupportive legal landscape”, “long administrative authorisation process”, “stringent regulations”, “compliance may be difficult”	11	50%

4.4.5.2.1 Perceived technical challenges

The most frequently mentioned challenge related to the use of MSW as RDF as an alternative to coal in cement manufacturing includes concerns regarding meeting the quality specifications of cement. Approximately 55% of respondents mentioned that they are concerned about “poor quality”, “meeting quality specifications”, “technical specifications of cement being insufficient”, “not meeting chemical standards”, “inconsistent calorific value”, “unknown fuel elements present in RDF” and “high chlorine concentrations in RDF” (Table 4-10).

Similar points were raised by the NCRR (1980) considering the experimental trials by Riverside Cement company in 1974 where an RDF to coal co-processing combination in excess of 40% RDF was tested (also see Section 2.7.1). The 1974 Riverside trial showed that fuel feeding challenges and temperature control issues were encountered. Similar quality issues were faced in the 1977 trial by Brownies Ferries Industry, where an RDF ratio beyond 40% reduced the cement’s strength, while increased particulate emissions were also an undesirable outcome (NCRR, 1980).

Compared to fossil fuels and end-of-life tyres, RDF from MSW tends to be highly heterogeneous and may contain significant quantities of alkaline metals and chlorine. Therefore, all applications using waste as a fuel need to thoroughly understand refuse material combustion and pollutant formation behaviour (Moreno *et al.,* 2022). This requires that MSW be separated at source, sorted into different categories, and mixed at optimal ratios to meet the energy needs for cement production, while also eliminating any sources of waste with undesirable characteristics. Five of the participants specifically mentioned that there is a lack of knowledge and understanding of the capabilities of MSW as RDF. One of the respondents mentioned that: *“There is a general lack of understanding of MSW as RDF and its capability as a fuel in cement production. This may cause hesitance towards replacing coal needs with MSW as RDF.”*

Respondents were also concerned about the monitoring requirements that may be related to using RDF instead of coal for cement production (mentioned by 41% of respondents) (Table 4-10). Comments were mostly related to additional emissions monitoring requirements and the infrastructure, and monitoring equipment needed for monitoring (also refer to the environmental challenge related to emissions from burning of RDF). One of the respondents specifically expressed their concern about the *“unavailability and cost of emissions monitoring for dioxins and furans, which may be generated when burning MSW”.* According to Bras *et al.* (2020) and Caillat *et al.* (2012), dioxins and furans (also referred to as PCDD/Fs) may form during the incomplete combustion of RDF. In the context of cement manufacturing, PCDD/Fs can be formed during the heating or pyrolysis of organic materials present in MSW, especially at too low temperatures. PCDD/Fs are classified as persistent organic pollutants in terms of the Stockholm Convention, and considered to be harmful pollutants and may have toxic or carcinogenic properties. As mentioned earlier, periodical monitoring of PCDD/Fs and other emissions are required in terms of NEMAQA’s list of activities in GNR. 893 (subcategory 5.5). The concern around PCDD/F monitoring is that South Africa has limited facilities to test PCDD/Fs and analysis are very expensive (Posthumus & Woollatt, 2014).

Lastly, 23% of the respondents mentioned that the incompatibility of cement kilns with RDF may be a challenge (Table 4-10). Utilising RDF for cement production requires modifications, such as fuel burners (pre-calciner) and a pneumatic feed system. Most South African kilns, especially the long dry kilns without pre-heating or exit gas conditions, do not have the necessary feeding systems to accommodate RDF (Karstensen, 2007). Replacing or modifying existing kilns to meet RDF feeding requirements was also mentioned as a financial challenge (see Section 4.4.5.2.2) below.

4.4.5.2.2 Perceived financial/economic challenges

Implementing RDF in cement production may require investments in equipment and technology to modify existing kilns, as mentioned in Section 4.4.5.2.1 above. The most frequently mentioned challenge related to the use of RDF was the cost of infrastructure (mentioned by 77% of respondents) (Table 4-10). Participants mentioned that “pneumatic fuel feed systems are expensive’’ and that the “cost of infrastructure such as RDF storage and feed systems may be prohibitively expensive”.

Four of the respondents (18%) mentioned concerns about the availability and cost of waste (once waste is regarded as having value) (Table 4-10). These participants mentioned the cost of procuring and processing suitable waste materials and mentioned that the *“price of waste may go up”* and that *“waste may become too expensive as a fuel, once the demand for it is high”*. As mentioned by Nahman (2011), if the economic feasibility of using waste as a resource (i.e. RDF) is not well-established, industries may be reluctant to make the switch from coal to MSW as a fuel.

4.4.5.2.3 Perceived environmental challenges

When comparing Table 4-9 and Table 4-10, it is clear that the perceived environmental opportunities outweigh the perceived environmental challenges of using RDF in cement manufacturing. Only one category of environmental challenge was mentioned by respondents, namely emissions from the burning of MSW (mentioned by 32% of respondents) (Table 4-10). Respondents were particularly concerned about "plastic burning", "release of toxic emissions", "dioxins and furans", "organic pollutants" and the release of "carcinogens". This challenge also relates to the monitoring requirements, mentioned as a technical challenge, as discussed in Section 4.4.5.2.1 above.

Herrero *et al.* (2018), in a report prepared for the European Commission on the use of AF in Spain, argued that AFs may reduce GHG and toxic emissions, however, there are concerns around the increase in emission of volatile organic compounds and mercury. Nonetheless, one can argue that RDF is man-made, and can be rationed and optimised to control the nature of carbon and other physico-chemical characteristics (through the sources of waste and the ratios thereof in RDF).

4.4.5.2.4 Perceived policy and licencing challenges

Half of the respondents (11 or 50%) mentioned that the current legislative framework presents difficulties in licencing waste co-processing or thermal treatment of waste. Participants were concerned about the "unsupportive legal landscape", "long administrative authorisation process", "stringent regulations" and the fact that "compliance may be difficult". One of the participants mentioned that *"The current licencing processes take a lot of time and enforcement of environmental conditions may be difficult and expensive (monitoring). There is also generally little support from government as far as authorisation processes and legal requirements are concerned".* This concern is also supported by the responses to Statements 3.4 to 3.6 of the survey questionnaire (see discussions in Section 4.4.2 above) where respondents indicated that the authorisation processes are difficult and ineffective, and that government support is generally lacking. Gale, (2021) highlighted that governments and global organisations consistently engage in a cyclical pattern of climate change discussion with little practical solutions and as a result, lack of sufficient support at national, provincial and local levels is also a concern highlighted by Shehata *et al.* (2022).

4.5 Chapter summary

This chapter has presented and discussed results related to three research objectives. RO1 and RO2 reported and discussed the results of laboratory analysis, while RO3 discussed the results of a survey questionnaire completed by 22 cement manufacturing industry experts.

Based on the testing of three samples with different paper-to-plastic rations, the results of RO1 and RO2 indicate that MSW as RDF may be a suitable alternative to coal in cement manufacturing. However, because of the heterogenous nature of MSW, waste sorting and drying becomes imperative in order to guarantee a fuel material balance that will qualify MSW as an alternative fuel. Furthermore, the feedstock needs to be mixed to a specific ratio to provide the suitable operational, technical and environmental specifications.

Both challenges and opportunities related to the use of MSW in RDF in cement manufacturing are perceived by cement manufacturers. Perceived opportunities include increased kiln efficiency, improved innovation, reduced cost of cement production, reduced cost of waste management, reduced greenhouse gas emissions, promotion of landfill diversion, promotion of environmental sustainability, reduced fossil fuel (coal) dependency, pollution prevention, and bringing about positive changes in the public perception of waste. Perceived challenges include uncertainties around meeting quality specifications of cement, additional monitoring requirements, incompatibility of cement kilns, cost of infrastructure, supply and cost of waste (once it has value), unintended emissions from the burning of MSW, and difficulties in licensing.

Chapter 5 of this dissertation concludes the research and provides opportunities for improvement and opportunities for future research.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This research aimed to investigate the co-processing of municipal solid waste (MSW) as an alternative fuel in cement production in South Africa. To achieve this aim, the following research objectives were considered:

> **Research objective 1:** To analyse the physio-chemical properties of Refuse Derived Fuel (RDF) for the purposes of cement production.
>
> **Research objective 2:** To optimise the carbon benefit of RDF as a fuel in cement processing; and
>
> **Research objective 3:** To investigate the opportunities and challenges for using MSW as RDF in cement production.

Section 5.2 provides the conclusions, while Section 5.3 suggests recommendations related to the research.

5.2 Research conclusions

Section 5.2 concludes each of the research objectives, individually, in Sections 5.2.1 to 5.2.3.

Sub-sections 5.2.1 and 5.2.2 present conclusions based on the physical and chemical properties of three RDF samples, consisting of different ratios of paper and plastic, and the suitability of these characteristics for combustion in cement manufacturing. In Chapters 3 and 4, the researcher discussed the analysis of physical characteristics through proximate analysis and the chemical/elemental analysis through ultimate analysis – both in an accredited laboratory. As supported by Azam *et al.* (2019), Bras *et al.* (2020) and Thawani *et al.* (2022), these experimental methods are ideal because they are accurate, relatively inexpensive and can be accessed by fellow students with limited resources in future.

On the other hand, to curb waste management and landfill challenges, municipal solid waste management will need to actively involve various waste treatment methods. Just like exemplary economies like Sweden with less than 1% landfilling rate and more than 60 % thermal treatment of waste (Behzad *et al.*2020), South Africa will benefit from the use of Refuse Derived Fuel.

Sub-section 5.2.3 presents the conclusions related to RO3, which considered the perceptions of experts from the cement manufacturing sector regarding the use of MSW as RDF in cement production.

5.2.1 Conclusions related to RO1: To analyse the physio-chemical properties of MSW as RDF for cement production

Municipal solid waste (MSW) poses challenges as a direct substitute for coal in cement production due to its heterogeneous nature with unpredictable moisture content and density. Successful integration of MSW as refuse-derived fuel (RDF) in cement production requires preprocessing, incurring additional costs for sorting, drying, shredding, or granulation to achieve uniform size, density, and compactness.

For MSW-derived RDF to be suitable for cement production, it must meet specific criteria, including a moisture content below 15%, volatile dry matter exceeding 80%, ash content below 20%, and a net calorific value of at least 21 MJ/kg (Wotjecha *et al*., 2021; Ohunakin *et al*., 2013), aligning with South African cement kiln standards. Optimal characteristics for a coal-to-RDF replacement ratio exceeding 30% are defined by these specifications.

The study's examination of three samples with varying paper-to-plastic ratios revealed that Sample 2 (40:60 paper:plastic) and Sample 3 (50:50 paper:plastic) align with RDF specifications for cement production. However, Sample 1 (60:40 paper:plastic) is less desirable due to higher ash and undesirable sulphur content.

From a calorific value perspective, RDF meets the technical requirements for an alternative fuel in cement production, with samples ranging from 27 MJ/kg to 30.4 MJ/kg, surpassing the minimum values required by local cement kilns (NPC and PPC). However, caution is warranted regarding potential emissions from burning RDF with a high volatile matter content, which ranged between 79.48% and 87.64% in the three samples.

While RDF exhibits combustion characteristics superior to coal, the crucial control of heavy metals and elements in cement manufacturing is highlighted. Excessive sulphur can compromise clinker pH, chlorine acts as a corrosive agent, and nitrogen dioxide, a harmful greenhouse gas, requires control. The analysed RDF samples' chlorine content (0.13% to 0.17%) falls within the acceptable range proposed by cement manufacturers. Sample 2 (0.23%) and Sample 3 (0.15%) meet sulphur content criteria, but Sample 1 (sulphur content: 0.58%) slightly exceeds cement kiln specifications.

Overall, with proper preprocessing and adherence to specified criteria, MSW-derived RDF can be a viable substitute for coal in cement production, offering a more sustainable and environmentally friendly alternative.

5.2.2 Conclusions related to RO2: To optimise the carbon benefit of RDF as a fuel in cement processing

To optimise the carbon benefit of RDF as a fuel, the net calorific value (CV), synthetic CO_2-eq per tonne (relative to coal) and, ultimately, CO_2 saved per tonne (%) (relative to coal) are important considerations. This means that a balance needs to be struck between the biogenic carbon (paper) and synthetic carbon (plastic) content of RDF. An RDF sample with a higher synthetic content (in this case, plastic) will have a higher potential for CO_2 emissions, while RDF with a higher biogenic carbon content (in this case, paper) will produce a higher ash content. The three samples tested included a 60:40 biogenic: synthetic carbon ratio (Sample 1), a 40:60 biogenic: synthetic carbon ratio (Sample 2) and a 50:50 biogenic: synthetic carbon ratio (Sample 3). This conclusion is consistent with the findings by Johnke *et al* (1992), where they stated that $C0_2$ is a carbon relevant gas whose effect in waste incineration is significant to the amount of 1.2 mg $C0_{2\text{-}eq}$ for every Mg of CO_2 emitted.

RDF has a relatively higher carbon content than coal. According to Nowak (2013), coal has 65.5% carbon content, which results in high CO_2 emissions (94.6 tonnes/TJ) (Imran *et al*., 2014). The CO_2-equivalent of the three samples tested was 70.6 tonnes/TJ (Sample 1), 74.8 tonnes/TJ (Sample 2), and 72.9 tonnes/TJ (Sample 3), respectively. The sample with the highest synthetic carbon (i.e. plastics) recorded the highest emissions factor concluding that plastics significantly affect the carbon benefit of RDF.

The results from this objective suggest that the production of cement can be done without having to rely heavily on fossil fuels such as coal. The carbon source of the fuel can be substituted with carbon sources, such as RDF (Azam *et al*., 2019).

Results related to RO2 suggest that, while Sample 1 (60:40 paper: plastic ratio) is the most suitable from an environmental point of view (CO_2 emissions savings), Sample 3 (with a 50:50 biogenic: synthetic carbon ratio) was the most appropriate RDF alternative for cement manufacturing from an operational and technical perspective (see Table 4-6). This is because Sample1 had a high sulphur content and undesirable ash content, which was outside of the acceptance criteria proposed by South African cement kilns.

5.2.3 Conclusions related to RO3: To investigate the opportunities and challenges for using MSW as RDF in cement production.

Perceived opportunities and challenges for using MSW as RDF in cement production were identified by distributing survey questionnaires to cement manufacturing industry experts. When reflecting on the overall responses from the 22 participants who are professionals in the South

African cement manufacturing sector, it is perceived that RDF is an appropriate alternative to coal for cement manufacturing purposes, especially from an operational, environmental, and economic perspective.

While the necessary legal (policy and authorisation) framework exists for the use of RDF in cement production, respondents however believe that more can be done to make the authorisation processes easier and more efficient. The respondents also believe that the government can do more to encourage the use of MSW as RDF in cement production.

Both challenges and opportunities related to the use of MSW in RDF in cement manufacturing are perceived by cement manufacturers. As supported by different researchers such as Hemidat *et al*. (2019) and Azam *et al.* (2019), perceived opportunities include increased kiln efficiency, improved innovation, reduced cost of cement production, reduced cost of waste management, reduced greenhouse gas emissions, promotion of landfill diversion, promotion of environmental sustainability, reduced fossil fuel (coal) dependency, pollution prevention, and bringing about positive changes in the public perception of waste.

Perceived challenges identified by respondents include uncertainties around meeting quality specifications of cement, additional monitoring requirements, incompatibility of cement kilns, cost of infrastructure, supply and cost of waste (once it has value), unintended emissions from the burning of MSW, and difficulties in licensing.

Of the five kilns represented in the research, only two have modern kilns with burners and feed systems that are suitable for accommodating RDF. This suggests that there are infrastructural challenges that need to be addressed to improve the use of RDF in the kins. The modern rotary kiln has features such as pre-heater and fuel-feeding systems that make them ideal for processing MSW (Karstensen, 2007). Some of the kilns are utilising alternative fuels such as end-of-life tyres and waste sludge. The use of MSW as RDF in cement manufacturing in South Africa has not yet been fully realised.

Issues like pollution pose genuine threats to society, given that their impacts are not always tangible or easily measurable in terms of costs. Nahman (2011) contended this point in his study on pricing landfill externalities. Gupta *et al.* (2012) endorsed these conclusions, particularly regarding the inadvertent emissions resulting from the incineration of municipal solid waste (MSW). This process releases particulate matter containing toxic elements like zinc, chromium, and manganese, which can have adverse effects on both society and the environment.

5.3 Recommendations

The sections below provide practical recommendations for improving and optimising the use of MSW as an RDF in cement production (Section 5.3.1), and recommendations for further research (Section 5.3.2) are also provided.

5.3.1 Practical recommendations to optimise the use of RDF in cement production

The following subsection gives practical recommendations to industry practitioners and policymakers to optimise the use of MSW as an alternative fuel in cement production.

- **Consistent sizing for RDF**: Ensure that refuse-derived fuel (RDF) used in cement production maintains a consistent size, ideally less than 30 mm, for optimal effectiveness. While pelletized RDF offers the most uniformity, utilizing fluff RDF remains a cost-effective alternative, considering the higher energy consumption associated with the pelletisation process (Gendebien *et al*., 2003).

- **Quality criteria for RDF:** Adhere to specific quality criteria for RDF, including maintaining a moisture content below 15%, ensuring volatile dry matter exceeds 80%, limiting ash content to below 15%, and guaranteeing a net calorific value of at least 21 MJ/kg. Additionally, it is crucial to keep the chlorine content of RDF below 0.3% and the sulphur content below 0.5%.

- **Cost-effective bio-drying:** Implement bio-drying processes for RDF, as it proves to be more cost-effective than thermal drying methods. The moisture content of RDF plays a significant role in influencing calorific value and ash content, with lower moisture content contributing to a higher combustible fraction.

- **Optimal biogenic content:** Limit the biogenic content of RDF to not exceed 50%, as surpassing this threshold may disrupt sulphur content and increase ash content. Beyond a 40% RDF content in the RDF-to-coal combination, challenges related to feeding and combustion are reported. The recommended ratio is 50% biogenic to 50% synthetic carbon for optimal performance.

- **Addressing the implementation gap:** Address the perceived implementation gap within South Africa's policy and legislative framework for RDF utilisation in cement production. Facilitate public-private partnerships to co-fund material recovery facilities (MRFs), which efficiently separate municipal solid waste, enabling the production of sustainable RDF for use in cement kilns.

- **Public-Private-Social Partnerships (PPSP):** Foster Public-Private-Social Partnerships (PPSPs) (See Figure 5-1) as an ideal setup for the successful implementation of waste-to-energy projects. Such collaborations align with Sustainable Development Goals (SDGs) such as SDG 11 (sustainable cities), SDG 12 (Responsible Consumption and Production), and SDG 8 (Decent work and Economic Growth). This approach promotes environmental justice, democracy, and addresses social, economic, and environmental concerns.

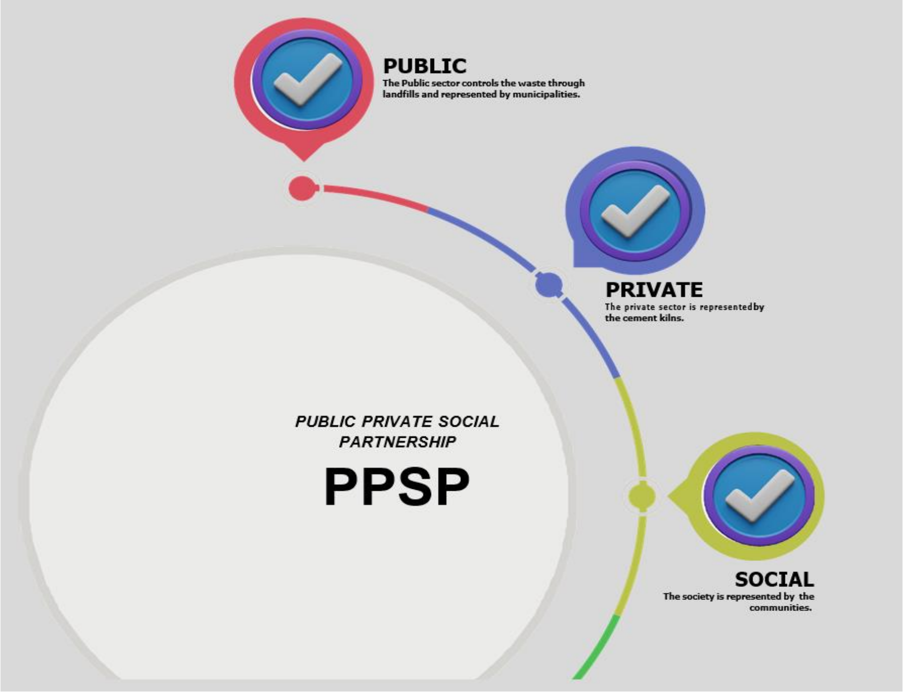

Figure 5-1: Public, Private, Social Partnerships (PPSP) (Special Economic Zone (Researcher's own conceptualisation).

- **Environmental Social Governance targets:** Leverage PPSPs to assist private sector cement factories in meeting their Environmental Social Governance targets, including SDG 13 (Climate Action) and SDG 7 (Clean water and energy). These programmes integrate universities into society, fostering research and development while bridging the gap between theoretical knowledge and practical implementation.

- **Community and municipal benefits:** Enable communities and municipalities to reap benefits from RDF projects by eliminating uncertainties around RDF quality and promoting waste recycling. Municipalities can establish MRFs benefiting from infrastructure that supports waste recycling instead of resorting to landfilling.

5.3.2 Recommendations for further research

The following are recommendations for further research:

- **Research on addressing high sulphur content:** Researchers should explore potential solutions to reduce the sulphur content of RDF containing more than 50% biogenic material.

- **Kiln testing of MSW as fuel in cement production:** Researchers can assess the viability of RDF derived from MSW in South Africa by conducting trials at the kiln to establish actual operational, technical and environmental efficiency.

- **Comprehensive Life Cycle Assessment (LCA):** While RDF may effectively substitute coal, drawing conclusions solely from laboratory tests, is insufficient. To comprehensively assess the environmental impact, researchers should conduct a Life Cycle Assessment (LCA) of RDF in cement production. LCA, an internationally standardized method, considers upstream and downstream inputs and emissions throughout the product or service life cycle, helping estimate greenhouse gas (GHG) emissions. International Organization for Standardization (ISO) standards, specifically the ISO 14040 series, guide the proper execution of an LCA.

- **Carbon sequestration technologies:** To further mitigate the carbon footprint of RDF, researchers should explore the implementation of carbon sequestration technologies. These technologies can convert CO_2 into ultra-low carbon and sustainable fuels like methanol or hydrogen.

- **Enhancing kiln efficiency for CO_2 reduction:** CO_2 emissions are influenced by both the carbon content of the fuel and the overall conversion efficiency of the kiln (Keller *et al.,* 2018). Researchers should focus on implementing advanced technological efficiency measures to reduce CO_2 emissions. Substantial efficiency increases can be achieved through the adoption of clean combustion technologies and combined cycle operation.

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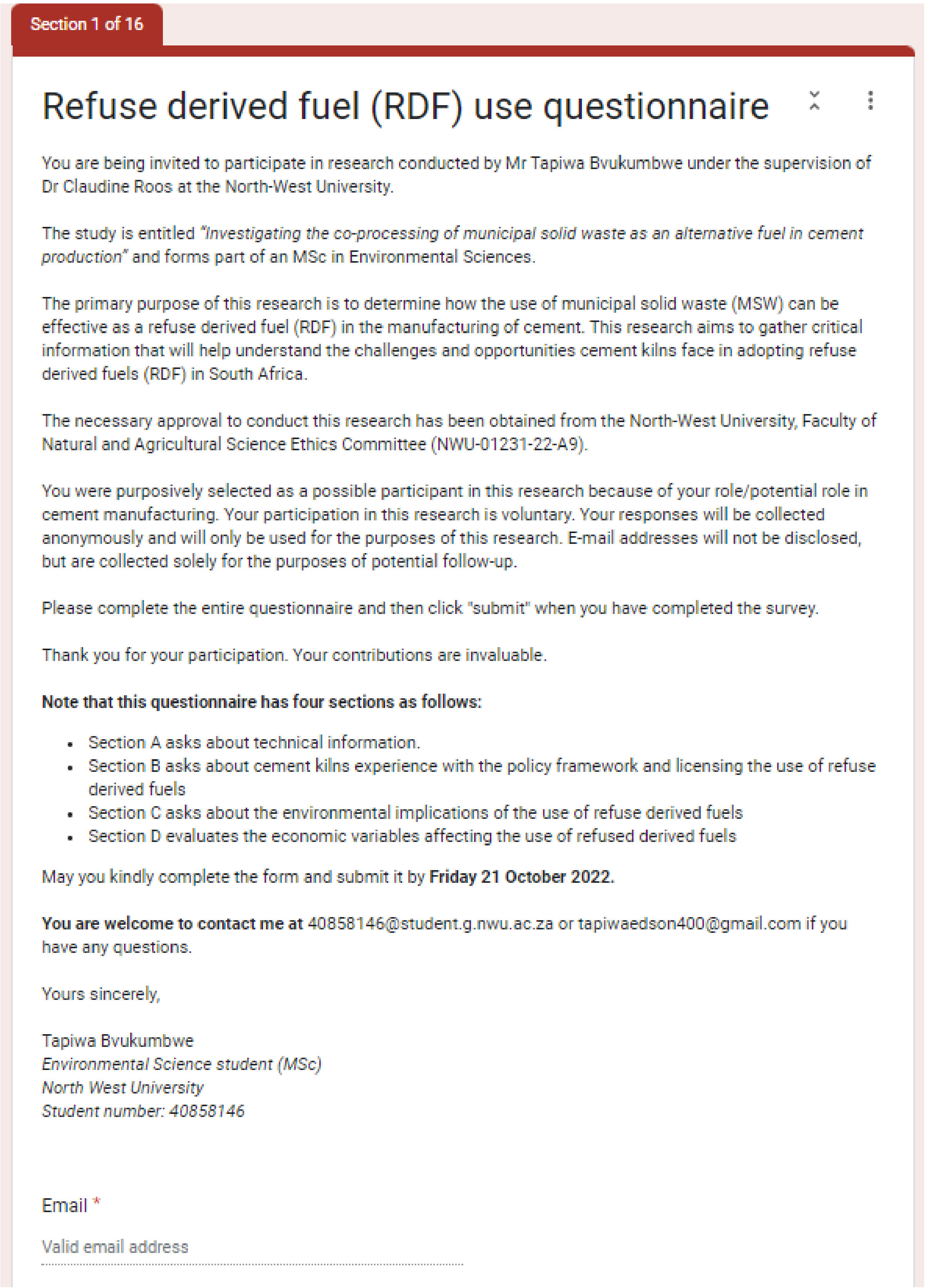
ANNEXUE A: SURVEY QUESIONNAIRE



Refuse derived fuel (RDF) use questionnaire

You are being invited to participate in research conducted by Mr Tapiwa Bvukumbwe under the supervision of Dr Claudine Roos at the North-West University.

The study is entitled *"Investigating the co-processing of municipal solid waste as an alternative fuel in cement production"* and forms part of an MSc in Environmental Sciences.

The primary purpose of this research is to determine how the use of municipal solid waste (MSW) can be effective as a refuse derived fuel (RDF) in the manufacturing of cement. This research aims to gather critical information that will help understand the challenges and opportunities cement kilns face in adopting refuse derived fuels (RDF) in South Africa.

The necessary approval to conduct this research has been obtained from the North-West University, Faculty of Natural and Agricultural Science Ethics Committee (NWU-01231-22-A9).

You were purposively selected as a possible participant in this research because of your role/potential role in cement manufacturing. Your participation in this research is voluntary. Your responses will be collected anonymously and will only be used for the purposes of this research. E-mail addresses will not be disclosed, but are collected solely for the purposes of potential follow-up.

Please complete the entire questionnaire and then click "submit" when you have completed the survey.

Thank you for your participation. Your contributions are invaluable.

Note that this questionnaire has four sections as follows:

- Section A asks about technical information.
- Section B asks about cement kilns experience with the policy framework and licensing the use of refuse derived fuels
- Section C asks about the environmental implications of the use of refuse derived fuels
- Section D evaluates the economic variables affecting the use of refused derived fuels

May you kindly complete the form and submit it by **Friday 21 October 2022.**

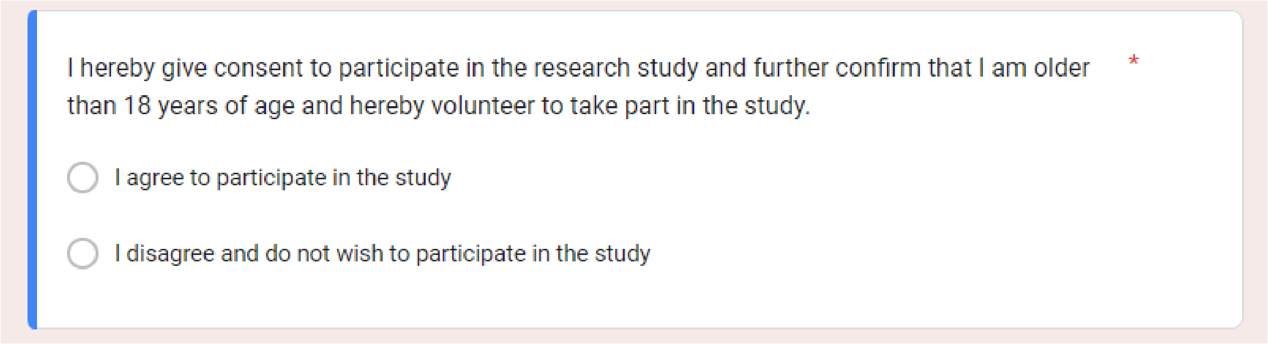
You are welcome to contact me at 40858146@student.g.nwu.ac.za or tapiwaedson400@gmail.com if you have any questions.

Yours sincerely,

Tapiwa Bvukumbwe
Environmental Science student (MSc)
North West University
Student number: 40858146

Email *

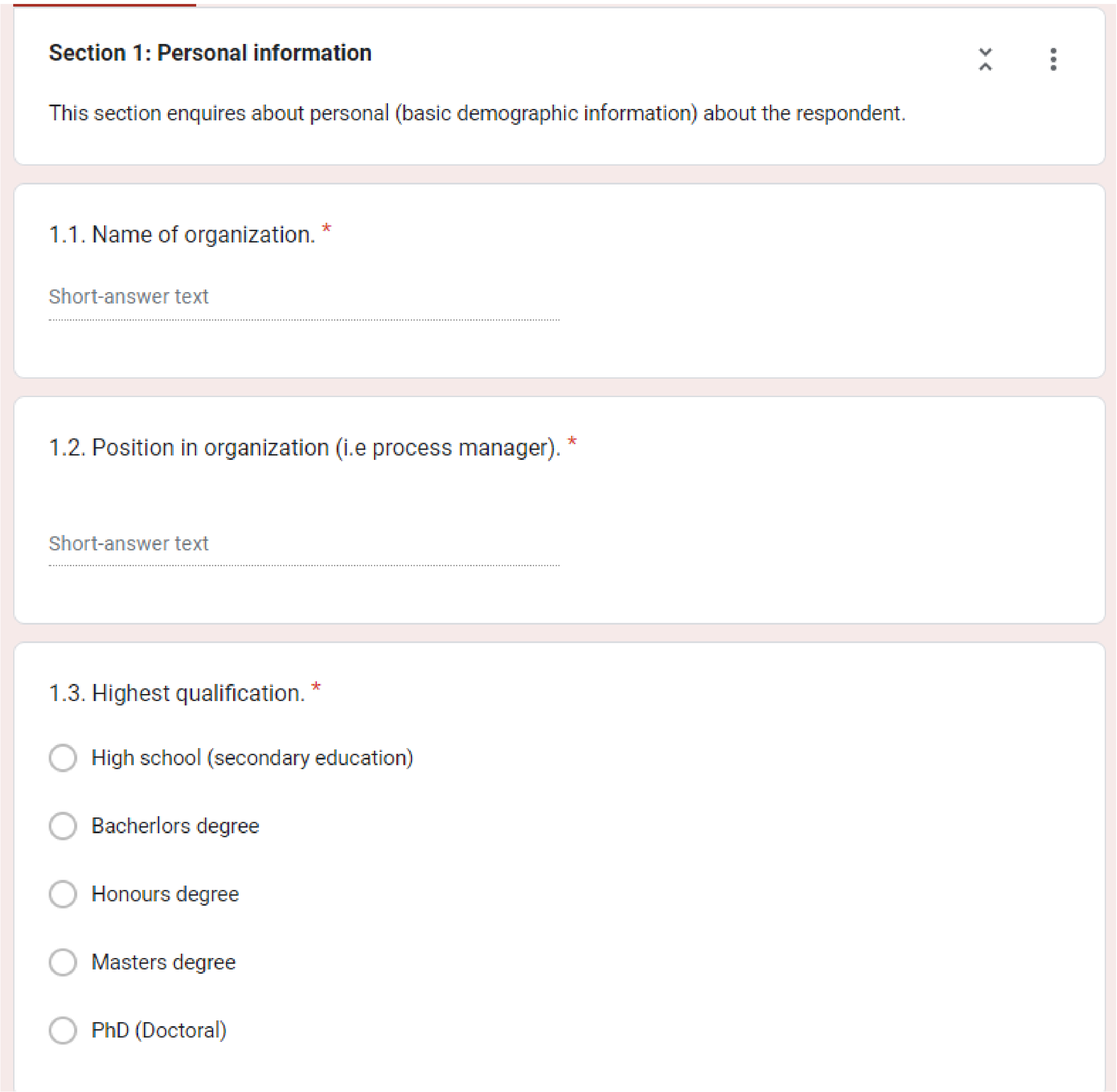
Valid email address



I hereby give consent to participate in the research study and further confirm that I am older than 18 years of age and hereby volunteer to take part in the study. *

○ I agree to participate in the study

○ I disagree and do not wish to participate in the study



Section 1: Personal information

This section enquires about personal (basic demographic information) about the respondent.

1.1. Name of organization. *

Short-answer text

1.2. Position in organization (i.e process manager). *

Short-answer text

1.3. Highest qualification. *

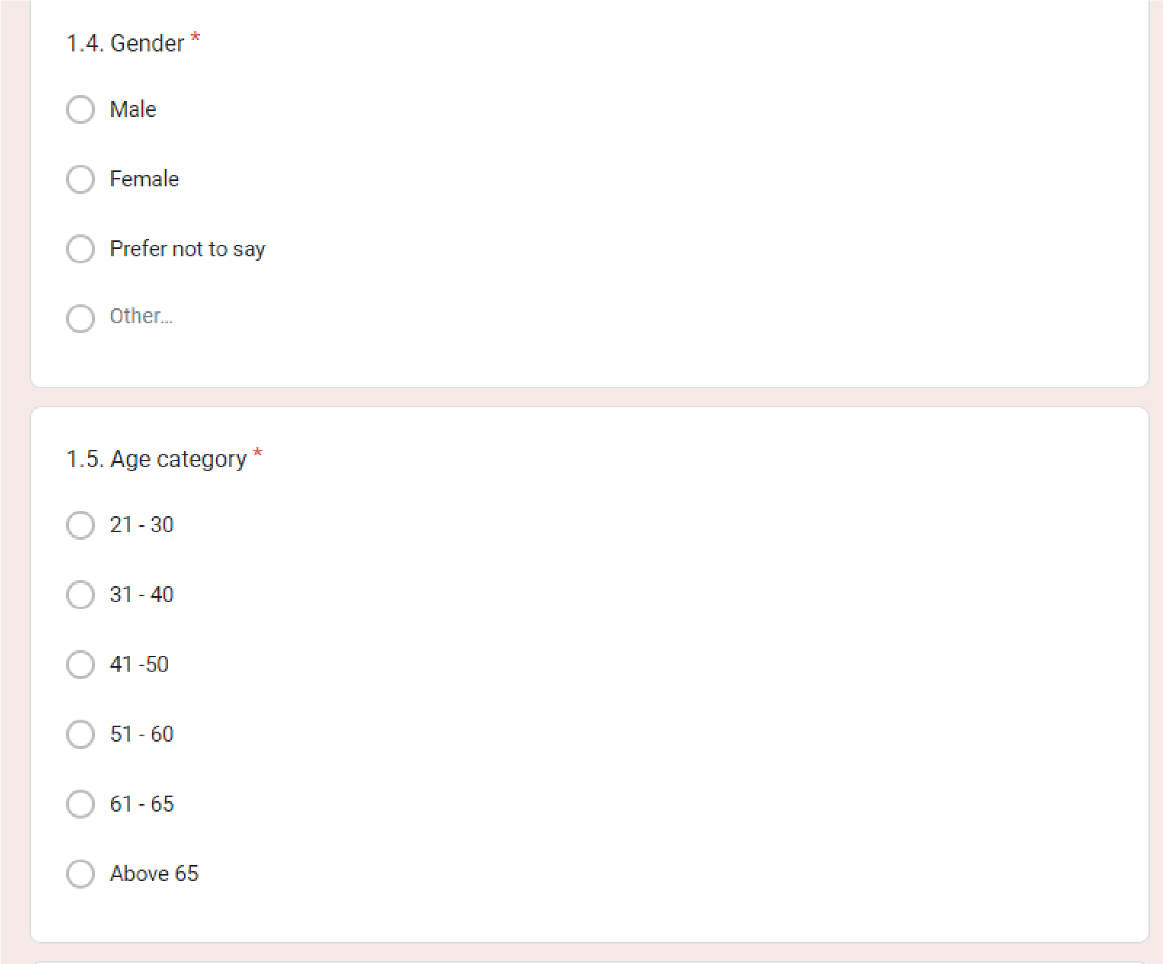
○ High school (secondary education)

○ Bacherlors degree

○ Honours degree

○ Masters degree

○ PhD (Doctoral)



1.4. Gender *

○ Male

○ Female

○ Prefer not to say

○ Other...

1.5. Age category *

○ 21 - 30

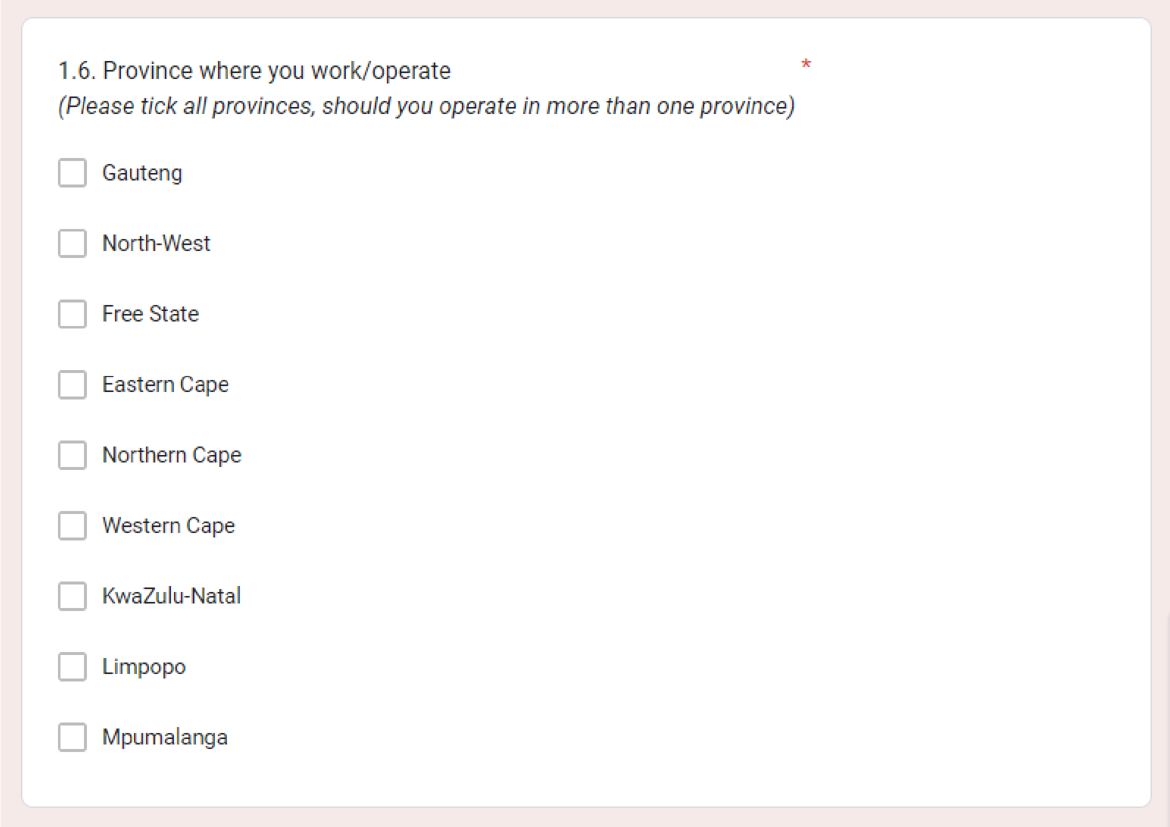
○ 31 - 40

○ 41 -50

○ 51 - 60

○ 61 - 65

○ Above 65



1.6. Province where you work/operate *
(Please tick all provinces, should you operate in more than one province)

☐ Gauteng

☐ North-West

☐ Free State

☐ Eastern Cape

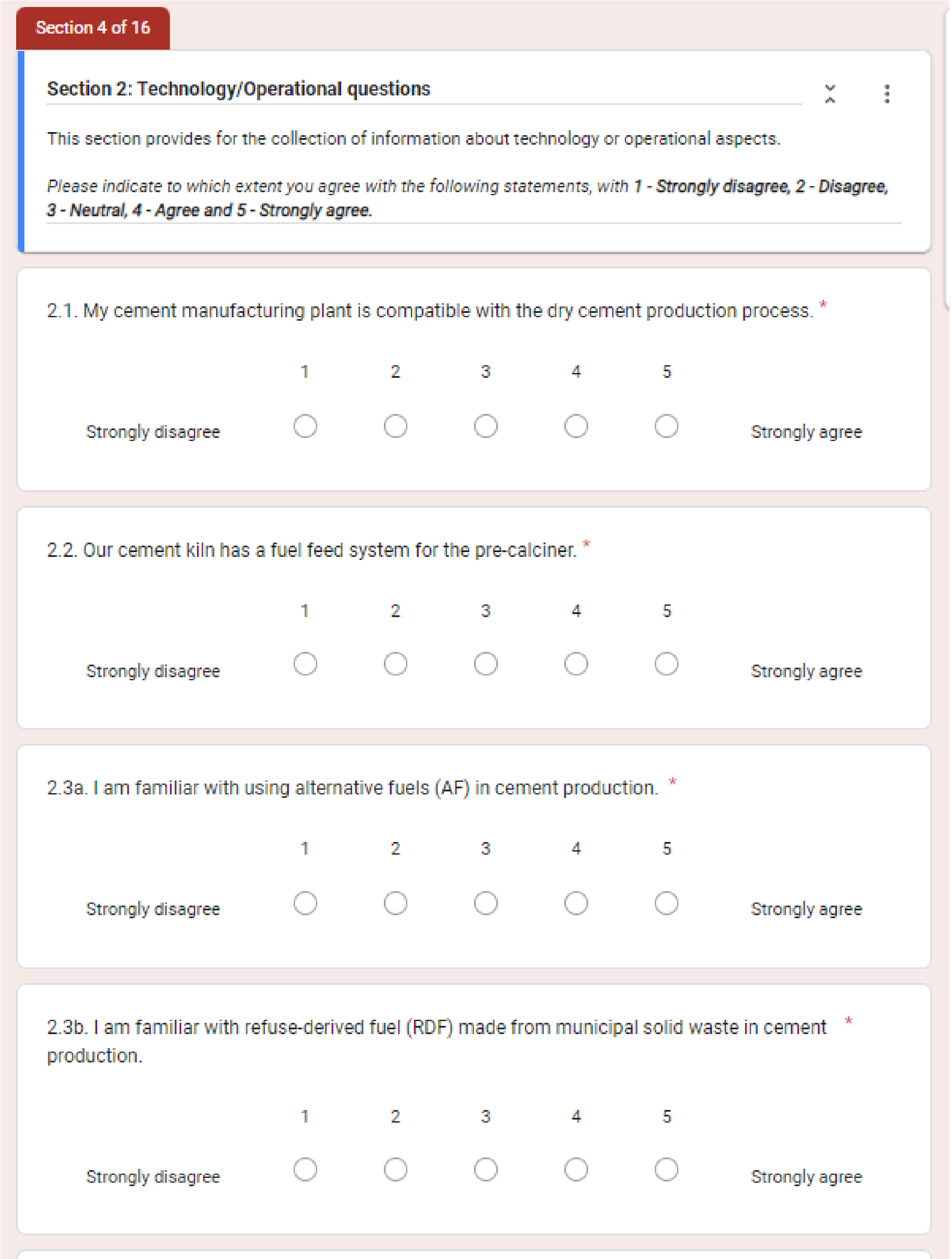
☐ Northern Cape

☐ Western Cape

☐ KwaZulu-Natal

☐ Limpopo

☐ Mpumalanga



Section 2: Technology/Operational questions

This section provides for the collection of information about technology or operational aspects.

*Please indicate to which extent you agree with the following statements, with **1 - Strongly disagree, 2 - Disagree, 3 - Neutral, 4 - Agree and 5 - Strongly agree.***

2.1. My cement manufacturing plant is compatible with the dry cement production process. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.2. Our cement kiln has a fuel feed system for the pre-calciner. *

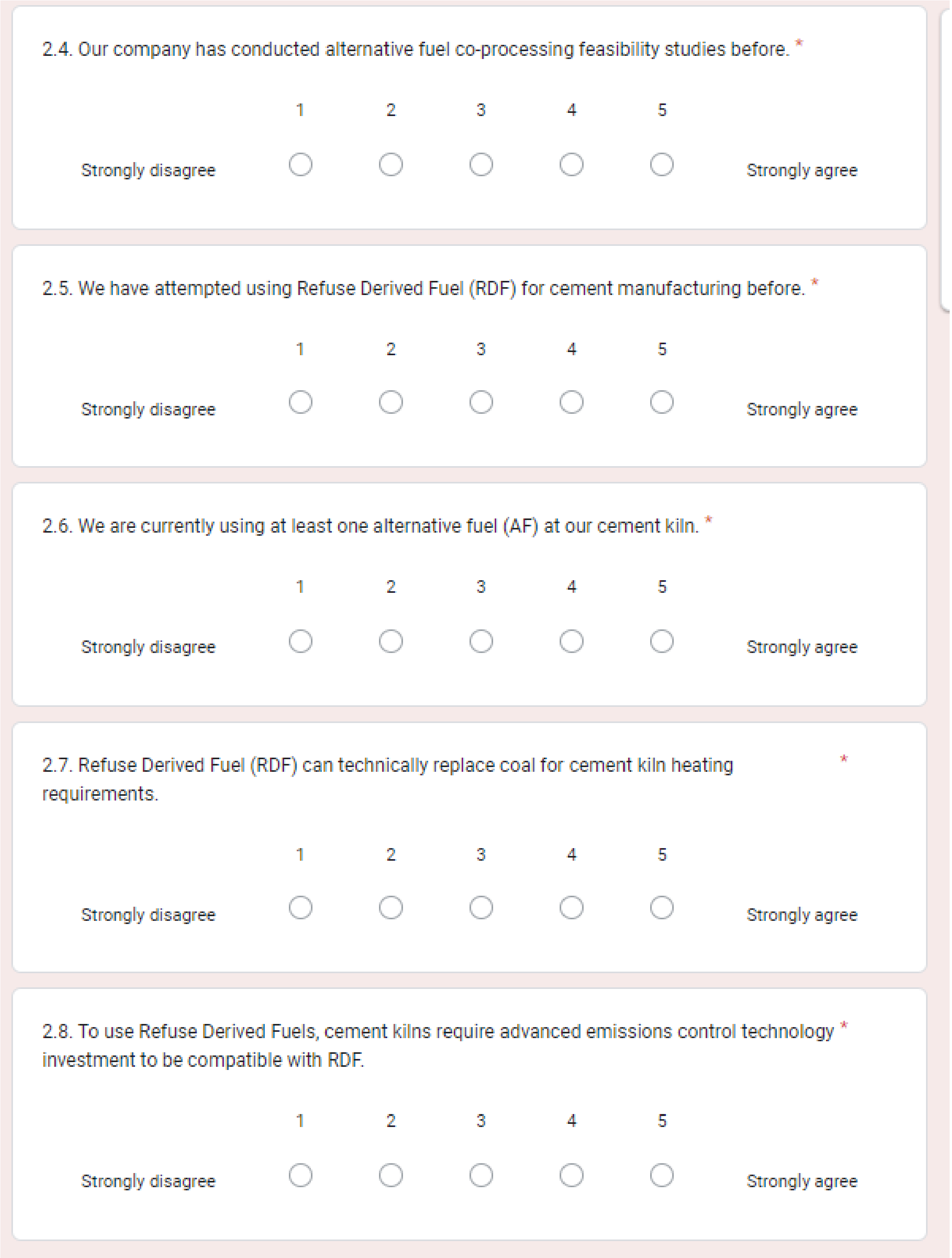
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.3a. I am familiar with using alternative fuels (AF) in cement production. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.3b. I am familiar with refuse-derived fuel (RDF) made from municipal solid waste in cement production. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



2.4. Our company has conducted alternative fuel co-processing feasibility studies before. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.5. We have attempted using Refuse Derived Fuel (RDF) for cement manufacturing before. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.6. We are currently using at least one alternative fuel (AF) at our cement kiln. *

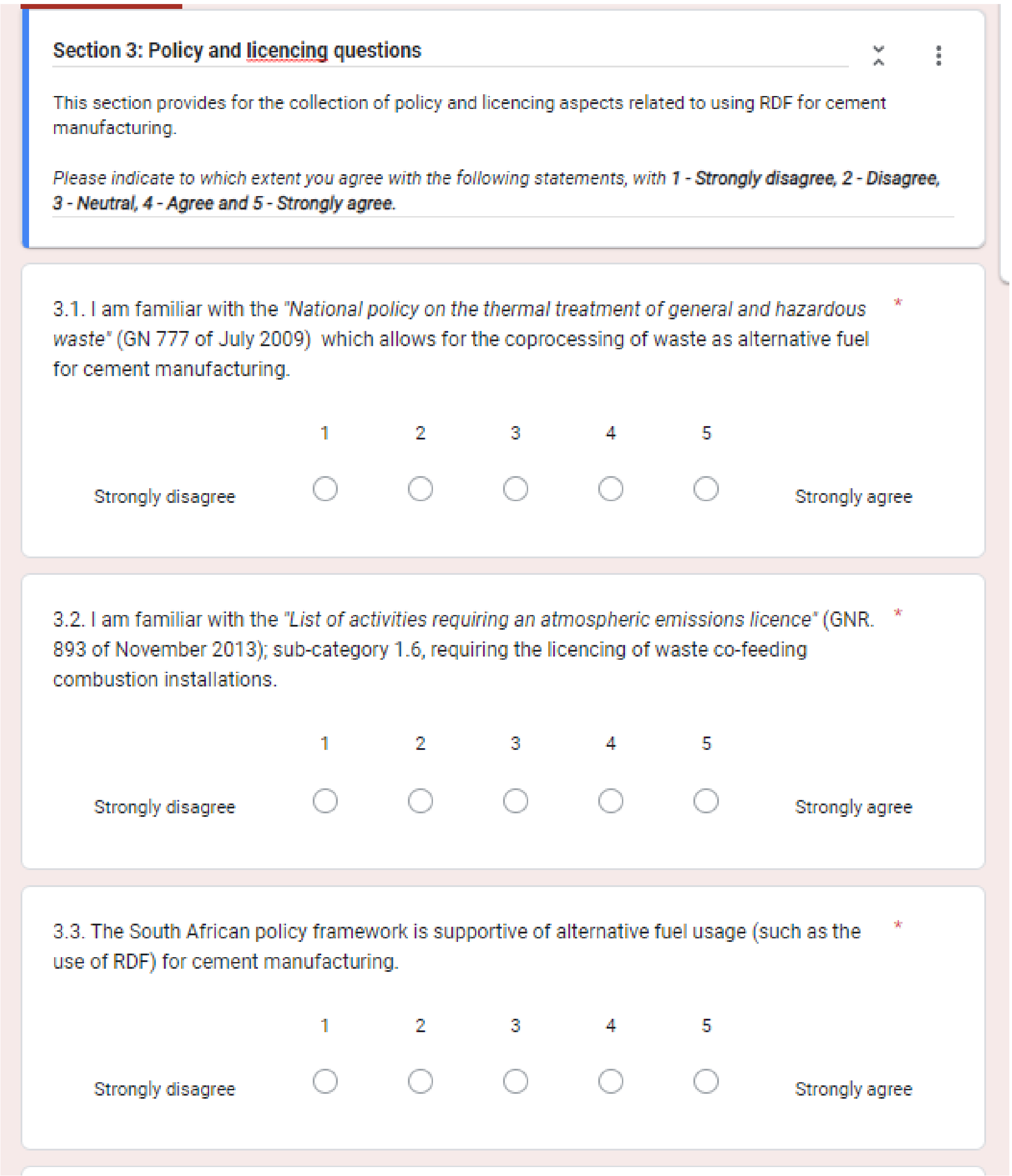
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.7. Refuse Derived Fuel (RDF) can technically replace coal for cement kiln heating requirements. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

2.8. To use Refuse Derived Fuels, cement kilns require advanced emissions control technology investment to be compatible with RDF. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



Section 3: Policy and licencing questions

This section provides for the collection of policy and licencing aspects related to using RDF for cement manufacturing.

Please indicate to which extent you agree with the following statements, with ***1 - Strongly disagree, 2 - Disagree, 3 - Neutral, 4 - Agree and 5 - Strongly agree.***

3.1. I am familiar with the "*National policy on the thermal treatment of general and hazardous waste*" (GN 777 of July 2009) which allows for the coprocessing of waste as alternative fuel for cement manufacturing. *

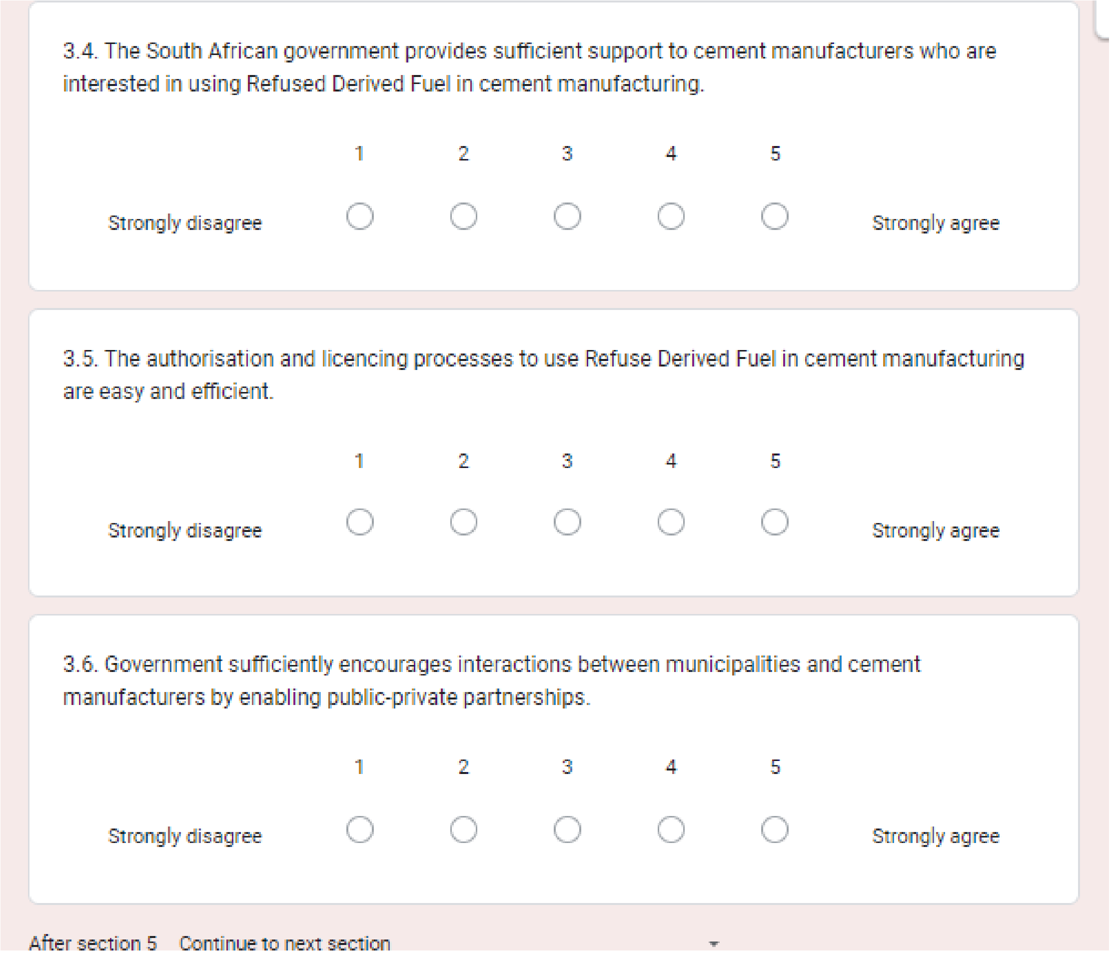
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.2. I am familiar with the "*List of activities requiring an atmospheric emissions licence*" (GNR. 893 of November 2013); sub-category 1.6, requiring the licencing of waste co-feeding combustion installations. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.3. The South African policy framework is supportive of alternative fuel usage (such as the use of RDF) for cement manufacturing. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



3.4. The South African government provides sufficient support to cement manufacturers who are interested in using Refused Derived Fuel in cement manufacturing.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

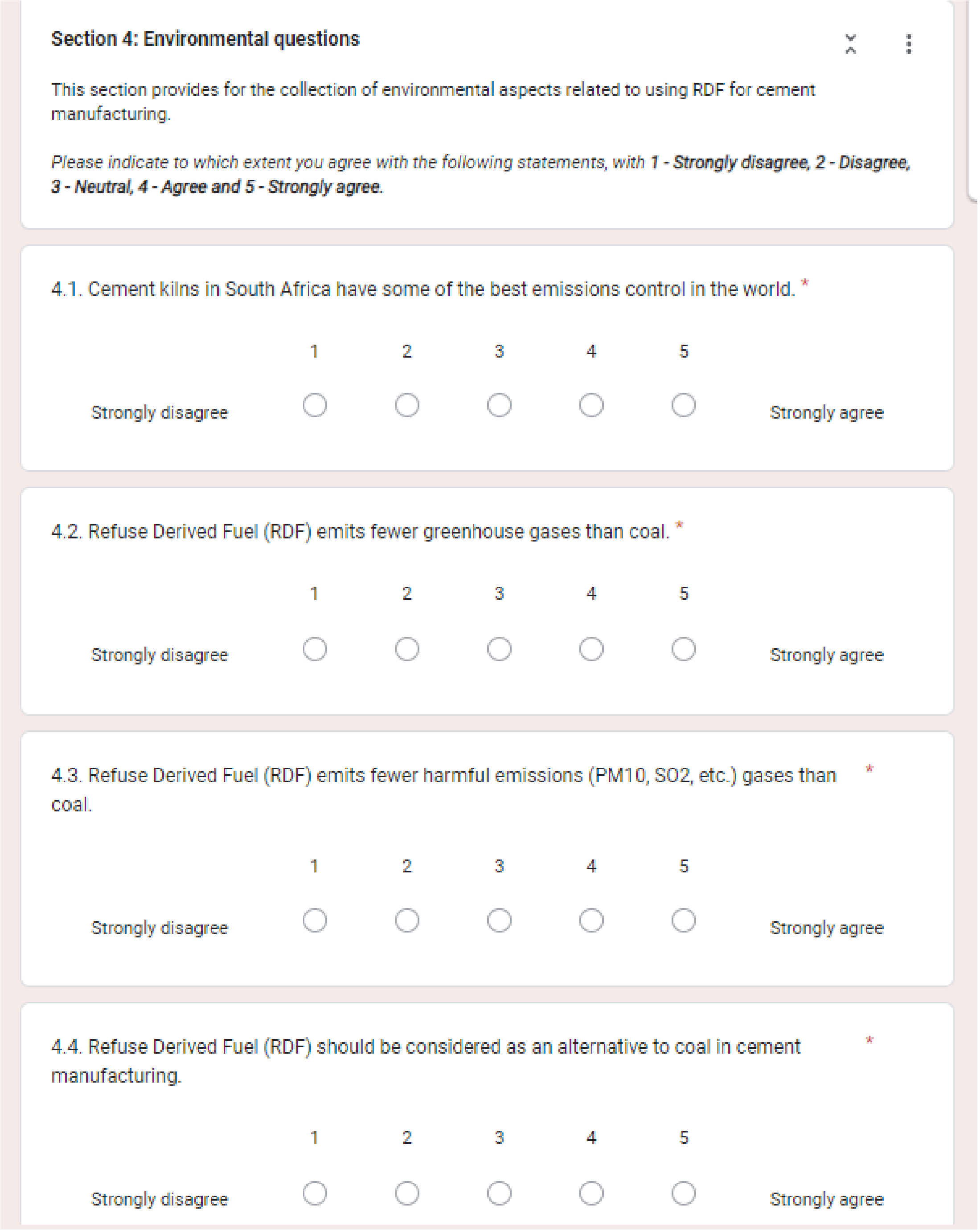
3.5. The authorisation and licencing processes to use Refuse Derived Fuel in cement manufacturing are easy and efficient.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.6. Government sufficiently encourages interactions between municipalities and cement manufacturers by enabling public-private partnerships.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 5 Continue to next section



Section 4: Environmental questions

This section provides for the collection of environmental aspects related to using RDF for cement manufacturing.

*Please indicate to which extent you agree with the following statements, with **1 - Strongly disagree, 2 - Disagree, 3 - Neutral, 4 - Agree and 5 - Strongly agree.***

4.1. Cement kilns in South Africa have some of the best emissions control in the world. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.2. Refuse Derived Fuel (RDF) emits fewer greenhouse gases than coal. *

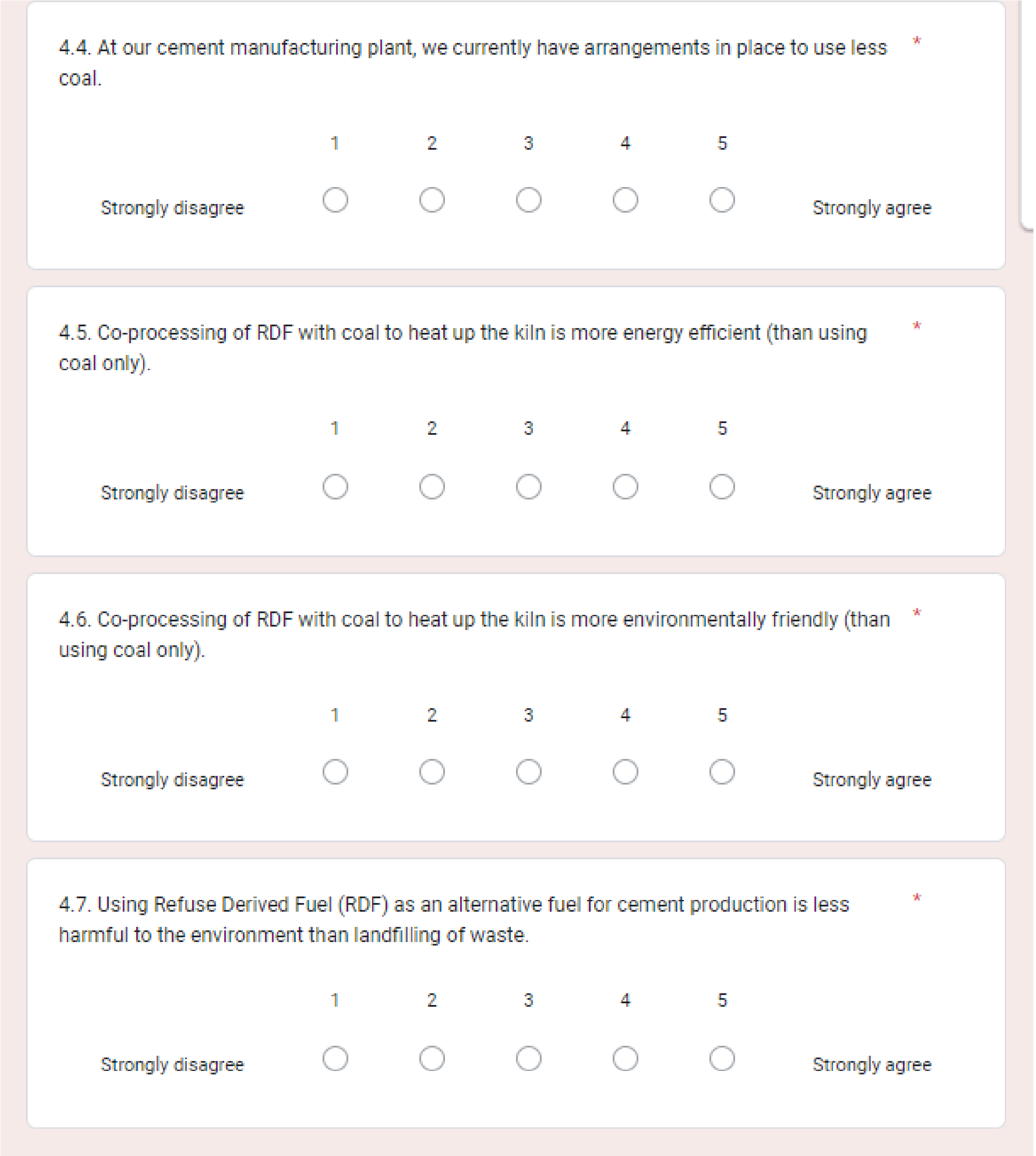
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.3. Refuse Derived Fuel (RDF) emits fewer harmful emissions (PM10, SO2, etc.) gases than coal. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.4. Refuse Derived Fuel (RDF) should be considered as an alternative to coal in cement manufacturing. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



4.4. At our cement manufacturing plant, we currently have arrangements in place to use less coal. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.5. Co-processing of RDF with coal to heat up the kiln is more energy efficient (than using coal only). *

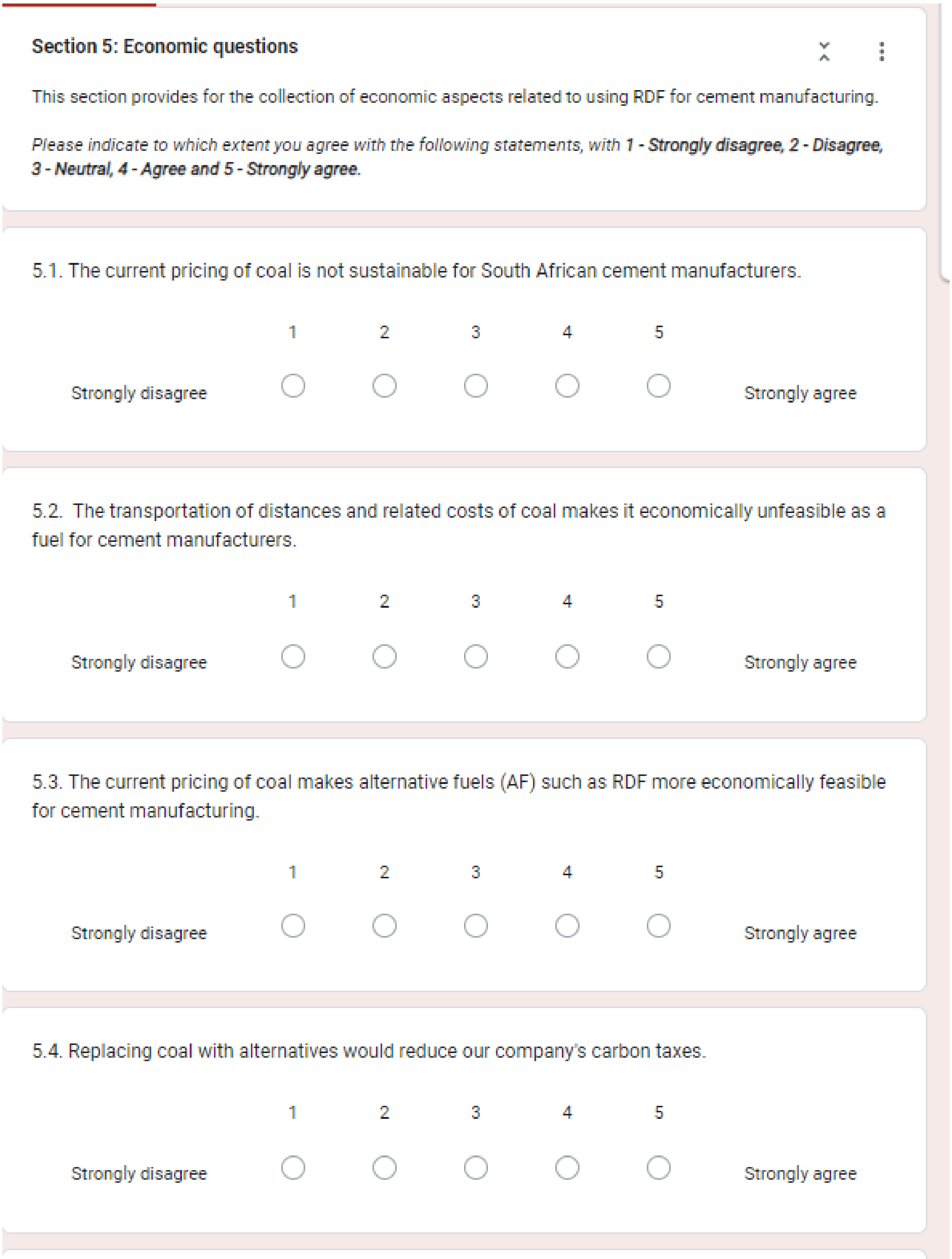
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.6. Co-processing of RDF with coal to heat up the kiln is more environmentally friendly (than using coal only). *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.7. Using Refuse Derived Fuel (RDF) as an alternative fuel for cement production is less harmful to the environment than landfilling of waste. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



Section 5: Economic questions

This section provides for the collection of economic aspects related to using RDF for cement manufacturing.

Please indicate to which extent you agree with the following statements, with ***1 - Strongly disagree, 2 - Disagree, 3 - Neutral, 4 - Agree and 5 - Strongly agree.***

5.1. The current pricing of coal is not sustainable for South African cement manufacturers.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.2. The transportation of distances and related costs of coal makes it economically unfeasible as a fuel for cement manufacturers.

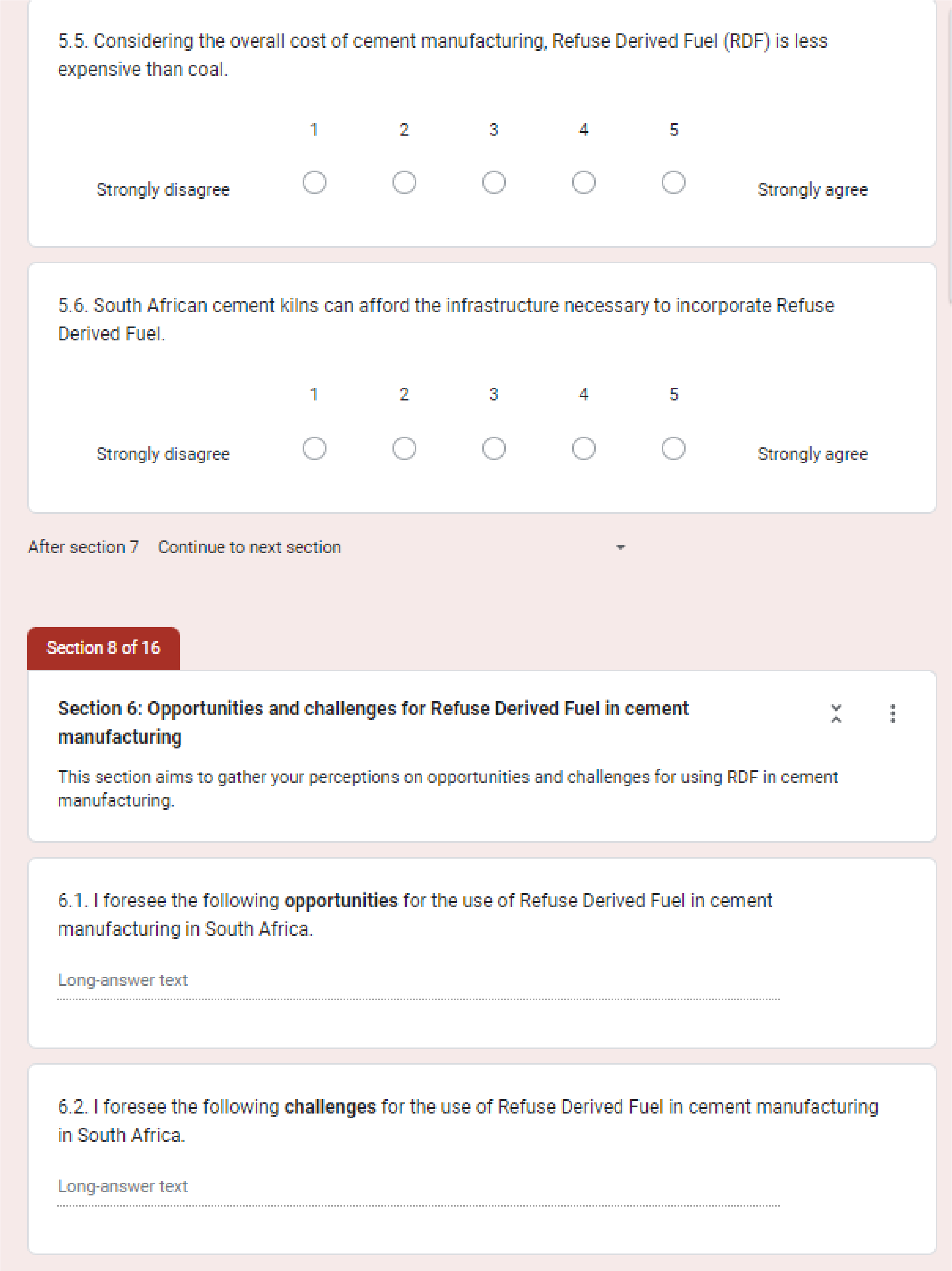
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.3. The current pricing of coal makes alternative fuels (AF) such as RDF more economically feasible for cement manufacturing.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.4. Replacing coal with alternatives would reduce our company's carbon taxes.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



5.5. Considering the overall cost of cement manufacturing, Refuse Derived Fuel (RDF) is less expensive than coal.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.6. South African cement kilns can afford the infrastructure necessary to incorporate Refuse Derived Fuel.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 7 Continue to next section

Section 6: Opportunities and challenges for Refuse Derived Fuel in cement manufacturing

This section aims to gather your perceptions on opportunities and challenges for using RDF in cement manufacturing.

6.1. I foresee the following **opportunities** for the use of Refuse Derived Fuel in cement manufacturing in South Africa.

Long-answer text

6.2. I foresee the following **challenges** for the use of Refuse Derived Fuel in cement manufacturing in South Africa.

Long-answer text