DEVELOPMENT OF COAL-LIKE REFUSED DERIVED FUEL FROM HAZARDOUS WASTE

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ORIGINAL LITERARY WORK DECLARATION

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DEVELOPMENT OF COAL-LIKE REFUSED DERIVED FUEL FROM HAZARDOUS WASTE

ABSTRACT

The quantity of the hazardous waste (HW) generated in Malaysia increased to 7,185 thousand metric tons from 4,013 thousand metric tons in 2019 This was primarily due to power plants and water treatment plants, and the rate of waste generation is likely to continue to rise as these are regarded as essential services. At present only about 30% of these wastes are subjected to recovery activities in Malaysia, where the focus is on material recovery. Many of the HW generated in Malaysia contains more than 8,000 kJ/kg of energy. These wastes can be a potential for energy recovery activities where refused-derived fuel (RDF) can be developed for a specific large volume application and as an alternative to coal. Therefore, RDF has been developed in this work using hazardous wastes and biomass mixtures to obtain solid fuel with coal-like characteristics. For this purpose, the Design of Experiment software was used where more than 500 RDF samples were synthesized using combinations of various wastes to determine the optimum product formulation. In this study, the RDF production process was developed by combining various processes of sorting, weighing, mixing, drying, and fused them together in a process called Thermo-biofusion. The optimum operating conditions of wastes and biomass mixture was identified in this study based on the calorific value (CV), volatile matter , fixed carbon, ash content as well as moisture content. The RDF developed had a CV of approximately 20,000 kJ/kg, moisture content between 15 to 20%, volatile matter, fixed carbon, and ash content of 32 %, 40 %, and 28 %, respectively. A production process was developed, and 1000 tones of RDF was produced and tested for potential utilization as a coal alternative in a cement manufacturing plant with varying RDF ratios, utilising the optimum recipe.

This study concluded that every ton of coal with 24,000 kJ/Kg CV could be replaced by approximately 1.5 tones of RDF. The maximum allowable limit of RDF usage was limited to 24% replacement to coal due to limitation on clicker quality and overall emission level. Emission levels of NOx were under the regulatory limit where at 5 ton/hour and 8 ton/hour of RDF feed, the levels of NO_X emitted are 356 mg/ Nm^3 and 301 mg/ Nm^3, respectively, values are lower than the regulatory limits in Malaysia. Heavy metal concentrations were also within the standard limit to prevent any threats to the environment. In terms of the efficiency of clinker and stack gas emission values, the substitution of 15 % of RDF to the coal at a feeding rate of 5 tons per hour in cement production did not cause any processing and quality issues in the existing cement production process. The study concluded that substituting 15 % of RDF with the coal in 1000 ton/day cement plant may reduce 112.8 USD/hour in operating cost. The advantages of co-combustion RDF with coal in the cement plant including reduction in the CO_2 emission, cost reduction of clinker production due to the usage of inexpensive fuel, and preservation of resources. This work has proven that by combining pre-selected hazardous wastes, mixture of biomass, and adding appropriate additives, a coal-like RDF can be produced for cement kiln application that meet the energy and emission requirements.

Keywords: *Alternative Fuel; Hazardous Waste; Waste Management; Carbon Footprint; Cement Factory; Economic Evaluation.*

PENGHASILAN BAHAN API TERBITAN BERCIRIKAN ARANG BATU DARIPADA SISA BERBAHAYA

ABSTRAK

Malaysia menghasilkan kira-kira 400,000 tan sisa berbahaya (HW) pada tahun 1987 dan jumlah itu meningkat kepada kira-kira 4 juta tan pada tahun 2020. Kadar penghasilan sisa berbahaya ini dijangka akan meningkat secara berterusan. Pada masa, ini hanya kira-kira 30% daripada sisa ini terlibat dalam aktiviti pemulihan di Malaysia, di mana tumpuan diberikan kepada pemulihan bahan. Majoriti HW yang terhasil di Malaysia mengandungi lebih daripada 8,000 kJ/kg tenaga. Sisa-sisa ini berpotensi bagi pemulihan tenaga, di mana bahan api terbitan (RDF) boleh dihasilkan untuk aplikasi berisipadu besar yang spesifik dan sebagai alternatif bagi arang batu. Maka, RDF telah dihasilkan di dalam kajian ini menggunakan campuran sisa berbahaya dan biojisim untuk mendapatkan bahan api pepejal bercirikan arang batu. Bagi tujuan ini, Reka Bentuk Eksperimen telah digunakan di mana lebih daripada 500 sampel telah dihasilkan menggunakan gabungan sisa-sisa untuk mengenal pasti formulasi produk yang optimum. Proses pembuatan RDF yang menggabungkan beberapa kaedah iaitu pengasingan, penimbangan, pengadukan, pengeringan, pengacuan dan penekanan campuran sisa dan biojisim pada keadaan operasi yang optimum turut dibangunkan dalam kajian ini. RDF yang dihasilkan mempunyai Nilai Kalori (CV) kira-kira 20,000 kJ/kg, kandungan lembapan antara 15 hingga 20%, bahan meruap, karbon tetap, dan kandungan abu masing-masing ialah 32%, 40% dan 28%. Dengan menggunakan resipi optimum dan proses pembuatan, 1,000 tan RDF telah dihasilkan dan diuji untuk potensi penggunaan sebagai alternatif bagi arang batu di loji pembuatan simen.

Kajian ini merumuskan bahawa setiap tan arang batu dengan CV sebanyak 24,000 kJ/kg boleh digantikan dengan kira-kira 1.5 tan RDF. Penggunaan maksimum RDF yang dibenarkan terhad kepada 24% penggantian bagi arang batu disebabkan oleh had ke atas kualiti batu hangus dan tahap emisi keseluruhan. Tahap emisi NOx berada di bawah had peraturan, di mana pada 5 tan/jam dan 8 tan/jam suapan RDF, tahap NOX yang dilepaskan masing-masing adalah 356 mg/Nm^3 dan 301 mg/Nm^3, iaitu nilai yang lebih rendah daripada had peraturan di Malaysia. Kepekatan logam berat juga berada dalam had piawai untuk mengelakkan potensi isu alam sekitar. Dari segi nilai kecekapan batu hangus dan emisi gas, penggantian 15% RDF bagi arang batu pada kadar suapan 5 tan/jam dalam pembuatan simen tidak menimbulkan sebarang isu kualiti dan pemprosesan dalam proses pembuatan simen sedia ada. Kajian ini merumuskan bahawa penggantian 15% RDF bagi arang batu dalam loji simen berkapasiti 1,000 tan/hari boleh mengurangkan kos operasi sebanyak 112.8 USD/jam. Maka, kajian ini membuktikan bahawa dengan menggabungkan beberapa jenis sisa berbahaya terpilih, sisa tidak berbahaya, biojisim dan bahan tambahan yang sesuai, RDF bercirikan arang batu boleh dihasilkan bagi aplikasi tanur simen yang memenuhi keperluan tenaga dan emisi.

Kata Kunci*: Bahan api alternatif; Sisa bahaya; Pengurusan Sisa; Jejak Karbon; Kilang Simen; Penilaian Ekonomi.*

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LIST OF SYMBOLS AND ABBREVIATIONS

CAT	:	Tricaine methanesulfonate
CAR		Environmental Quality (Clean Air Regulation)
CO_2 -eq		CO_2 equivalent
CHNOS		Analysis for determination of carbon, hydrogen, nitrogen, sulfur and oxygen content
CV		Calorific Value
DOE	:	Design of Expert
GHG	:	Greenhouse gases
IPCC		Intergovernmental Panel on Climate Change
LCA	:	Life Cycle Assessment
MSW		Municipal Solid Waste
RDF	:	Refused Derived Fuel
RSM	:	Response Surface Methodology
TTLC		Total Threshold Limit Concentration
VM		Volatile matter

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1. Background

Waste generation has emerged as the most serious concern in recent years because of growing urbanisation and population growth. According to statistical forecasts, the world will generate 3.4 billion tonnes of waste per year by 2050, a substantial increase from today's 2 million tonnes (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). According to the Greenhouse Gas Reporting Program, waste is one of the primary anthropogenic sources of greenhouse gas emissions, generating 10.3 million metric tonnes of CO_2 equivalent. Municipal landfills accounted for 82% of waste sector emissions, followed by solid waste combustion (8.8%), industrial landfills (7.4%), and wastewater treatment (1.8%).

Malaysia is one of the top carbon dioxides (CO_2) emitters in the ASEAN region, with a total of 225 million tons of CO_2 released in 2019. In combating the climate change issue, Malaysia signed both the Kyoto and Paris agreements in 1997 and 2015, respectively. According goal of Paris Agreement, Malaysia anticipates to reduce greenhouse gas emissions by 45 % based on its Gross Domestic Product (GDP) by 2030 (MESTEC, 2018). In 2021, the Malaysian Prime Minister assertively announced that a carbon tax is included in the 12th Malaysian Plan (2021-2025) where a fixed charge will be imposed on the greenhouse gas (GHG) emissions. Malaysia has developed a comprehensive set of legal provisions related to the management of hazardous wastes/scheduled waste (HWs). In the First Scheduled of the Environmental Quality Act in Malaysia, 77 categories of HWs have been defined. Sources of HWs in Malaysia were mainly from wastewater treatment plants, coal-fired power plants, chemical manufacturing operations, electroplating, and oleochemical industries (Muralikrishna &

Manickam, 2017). Following the National Environment Policy, the Malaysian Government has adopted scheduled waste policies at the waste generation point to the treatment and disposal facility. However the cost of HWs disposal in Malaysia is high-priced, and thus, there are many occurrences of illegal dumping cases in Malaysia (Noor, Yusof, & Nor, 2019).

Thermal treatment of HWs is one of the forthcoming solutions for obtaining cleaner renewable energy to replace fuel resources such as coal, natural gas, petroleum, and coke because (Sadala et al., 2019). HWs could be converted into refuse-derived fuel (RDF) by eliminating the non-combustible fraction, reducing its size and moisture content, homogenizing the waste, and recombining them (Sadala et al., 2019) The main advantages of RDF including higher thermal values, physical and chemical composition uniformity, simplicity, transport and storage, low emission rate, and more minor excess air requirements during combustion (Shangdiar, Lin, Cheng, Chou, & Wu, 2021).

On the other hand, cement manufacturing is an energy-intensive industry, accounting for nearly 35–40 percent of the total production costs and contributing almost 5 percent of total global industrial energy consumption (Ernst Worrell, Lynn Price, Nathan Martin, Chris Hendriks, & Meida, 2001). Cement manufacturing is also the primary source of CO_2 emission emitting approximately 8 % of global human-made CO_2 emissions (Pieper, Wirtz, Schaefer, & Scherer, 2021). Carbon dioxide emission from the production of cement clinker originates from the conversion of limestone ($CaCO_3$) into lime (CaO) and combustion processes (Kara, 2012). In this regard, RDF could serve as an environmentally sustainable alternative to conventional fuels with low carbon emissions without compromising the cement's quality (Robbie, 2018). Considering the worldwide cement production scale, even a slight decrease in the average global emissions per ton can reduce CO_2. Every 10% decrease in the cement CO_2 intensity by

2050 could save around 0.4 Gt CO_2 and substantially contribute to slowing climate change. Therefore, this study aimed to develop Refuse Derived Fuel (RDF) with high Calorific Value (CV) from different types of hazardous wastes. For the first time, the possible usage of RDF developed from hazardous waste in the cement manufacturing as a fuel substitute for coal has been investigated.

1.2. Problem Statement

Malaysia is the eighth largest importer of coal briquettes and the 12th largest importer of bituminous coal. Primary coal imported by Malaysia increased at an average annual rate of 14.6 percent from 3,397 thousand tonnes in 2000 to 37,959 thousand tonnes in 2019. Currently, Malaysia also imports as much as 98% of the coal to generate about 40% of the country's energy. The remaining supply is consumed by the cement, iron, and steel manufacturers. The country's thermal power plants run on coal because it is an inexpensive energy source for generating electricity. However, burning coal is subject to several externalities, like unfavourable impacts on the environment and public health, that is neither fully recognized nor internalized in the price of electricity.

Since Malaysia is a net importer of coal and coal products, finding an alternative source for coal is necessary. It is estimated that the demand for coal will be increased to 37.4 million Mt in 2030 (APEC Energy Overview, 2009). Because it relies on coal, the Malaysian Government will lock the country into a higher carbon emissions trajectory for years to come if it does not reassess its energy choices now. This is in noncompliance with the Paris Agreement commitments, which require countries to adopt long-term low-emission programs. The Malaysian Prime Minister assertively revealed in September 2021 that a carbon tax is included in the 12th Malaysian Plan (2021-2025). In line with this, in its 2019 proposal for a carbon tax in Malaysia, the Penang Institute recommended an introduction charge of RM35 per tCOe, rising to RM150 per tCOe by the end of 2030.

Recently, Refused Derived Fuel (RDF) has received worldwide attention and has become an interesting alternative to solve global warming and waste management problems. RDF is a potential substitution for conventional fossil fuels as it is a value-added material with a higher calorific value, homogenous particle size, and better exhaust gas emissions. RDF is partly carbon neutral and substituting RDF for coal will save cost and reduce CO_2 emissions. Waste can be sorted and subsequently turned into fuel suitable for conventional and industrial plants. Although, many research groups exploring to produce RDF in the past years; most investigations focused on the production of municipal solid waste (MSW) (Nutongkaew et al., 2014), waste tires (Wan, Chang, Chien, Lee, & Huang, 2008), and agriculture waste (Demirbaş, 2001). The use of hazardous industrial waste as the source of RDF production has yet been commercialized till today.

Henceforth, this work explores the existing technology to produce RDF with acceptable quality from hazardous industrial waste. Hazardous waste as the raw material to produce RDF is a relatively new concept and are largely untapped compared to using municipal solid waste to produce an alternative to fossil fuels such as RDF (Chand Malav et al., 2020; Han et al., 2021; Silva, Contreras, & Bortoleto, 2021). A great alternative to the area is the WtE (Waste to Energy) concept, in which RDF is developed from the mixture of hazardous waste. Biomass, from agricultural waste and energy crops, has long been used in power plants as a renewable fuel (Kardaś, Kluska, & Kazimierski, 2018; Shangdiar, Lin, Cheng, Chou, & Wu, 2020). The combination of hazardous waste and biomass can improve carbon emission, lower investment costs, and make the fuels more affordable, balancing environmental, economic, and social benefits (Xiong et al., 2017).

Hazardous waste may have a different CV value in the raw or untreated state. To accommodate this, modifications to the operating conditions, such as adjusting the feed rate of coal or altering the airflow into the cement kilns' must be made. Therefore, this study aims to develop RDF with a consistent CV, volatile matter, fixed carbon, and ash using the mixture of hazardous waste and biomass.

1.3. Research Questions

1. What waste properties that must be considered when determining potentially hazardous waste and biomass sources for RDF development?
2. What processes could be used to optimise RDF production using different types of waste?
3. How to evaluate the viability of RDF from hazardous waste as a coal substitute in cement manufacturing?
4. What are the environmental impact of RDF developed from hazardous waste utilization on environment?

1.4. Aim and Objectives of the Study

This study aimed to explore the development of RDF from mixed hazardous wastes and biomass to produce RDF with high CV to be used in cement manufacturing. Hence, the objectives of this study are as follows:

1. To identify and characterize possible sources of hazardous waste generated by Malaysia industries to develop RDF.
2. To develop and optimise refuse-derived fuel formulations with coal-like characteristics.

3. To evaluate the feasibility of using the RDF in cement manufacturing as an alternative to coal.
4. To quantify the greenhouse gas emission generated from the refuse derive fuel production.
5. To establish a protocol for the safe and efficient handling of fuel made from hazardous waste.

1.5. Novelty

The novelty of the work is in providing a clear strategy and know-how for developing a refused derived fuel with a consistent calorific value from a mixture of hazardous waste and biomass.

1.6. Justification of Work

The following are the primary justifications for developing RDF in this study:

i. To improve the value chain of industrial waste generated from various industries and biomass.
ii. In line with the Malaysian government to reduce CO_2 generation by 45% by the year 2030, RDF helps reduce the dependence on fossil fuels used in the country, bridging the gap towards the 45% target in the year 2030.
iii. Foreign Exchange Savings, where Malaysia imports almost 20 million Mt of coal and is forecasted to import nearly 35 million Mt in 2030. At the current world price of coal, this is almost RM6.0 billion worth of importation.
iv. Industrial waste, especially hazardous waste in Malaysia is not effectively recovered and or disposed of, where the waste is usually landfilled, solidified, and

or incinerated, which leads to greenhouse gas emissions. Thus, waste recovery is beneficial to the environment and economy.

1.7. Scope of the Study

This study focused on developing RDF from selected hazardous waste and biomass from Malaysian industries. The optimum formulation of RDF has been identified, and the optimized RDF has been utilized in cement manufacturing as an alternative to coal with predetermined ratios. The economic and environmental feasibility of newly developed RDF has been determined by considering the RDF production, coal replacement in cement manufacturing, and carbon dioxide emission quantification.

1.8. Significance of the Study

The knowledge gained from this study will contribute to producing quality fuels from hazardous waste. When combusted in the facilities such as cement kilns and power plants, these fuels will generate lower dioxin emissions, which could mitigate the environmental impact of the combustion process. A successful RDF from hazardous waste is a promising approach to convert solid waste into a standard solid fuel.

1.9. Thesis Outline

This thesis starts with an abstract followed by five chapters consisting of different aspects of the current study and ends with references and appendices.

Chapter 1: Introduction

This chapter describes the introductory aspect of the study, comprising the background of the research and the research problem statement. Based on the problem statement, the aim and objectives of the study are defined. The outline of the thesis is also included in this chapter.

Chapter 2: Literature Review

This chapter discusses the reviewed literature comprising the production of refuse-derived fuel from various types of waste, production processes, and the friendliness of refuse-derived fuel to the environment.

Chapter 3: Research Methodology

This chapter provides the methodology adopted in this study. It comprises waste characterization, formulation of RDF, production processes, refuse-derived fuel characterization, and methods used to estimate the amount of greenhouse gas emissions generated in producing refuse-derived fuel.

Chapter 4: Result and Discussion

This chapter describes the results obtained in this study. In this section, RDF characterization and the optimization of RDF and production processes are reported. Besides, the combustion processes and efficiencies of the RDF-coal mixtures at a certain percentage on an energy basis in the cement kiln are investigated. The clinker quality assessment using RDF also has been discussed in this section. Properties of the commercialized RDF were compared with the RDF developed in this study. The final section of this chapter discussed the economic and environmental feasibility of the RDF produced in this study.

Chapter 5: Conclusion

This chapter discusses the summary of this study and concludes remakes of the main findings. The recommendation for future work is also provided in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1. Types of Waste

Worldwide, economic and, population growth, urbanization and rising living standards have led to an increase of waste, and there are no signs that this trend will slow down any time soon. Moreover, as a result of industrial and healthcare facility expansion, large volumes of industrial and medical waste have entered the waste stream, posing severe environmental and human health risks. Waste materials are either liquid or solid form and they are classified by source and composition. The generation of waste is the inevitable consequence of all processes where materials are used. Solid Waste may be generated during the extraction of raw materials, processing of raw materials into intermediate and final products, consumption of final products, and other activities (Abdel-Shafy & Mansour, 2018).

According to the classification and labelling of toxic chemicals and preparations, waste can be divided into municipal solid waste (MSW), agricultural and animal waste, medical waste, radioactive waste, hazardous waste, industrial non-hazardous waste, construction and demolition debris, extraction and mining waste, oil and gas production waste, fossil fuel combustion waste, and sewage sludge (Millati et al., 2019). Developed countries, such as the United States, produce more waste because of economic activity, consumption, and population increase. Figure 2.1 shows the waste generation per capita of largest waste producing countries (Ian, 2021; Millati et al., 2019). In addition to municipal solid waste (MSW), the figures include industrial and medical waste as well as E-waste, hazardous waste, and agricultural wastes . Canada is the world's largest producer of waste per capita, as shown in Figure 2.1. In 2019, Canada produced 10 metric tonnes more than the United States per person. Meanwhile, the United States is the world's largest daily producer of MSW.

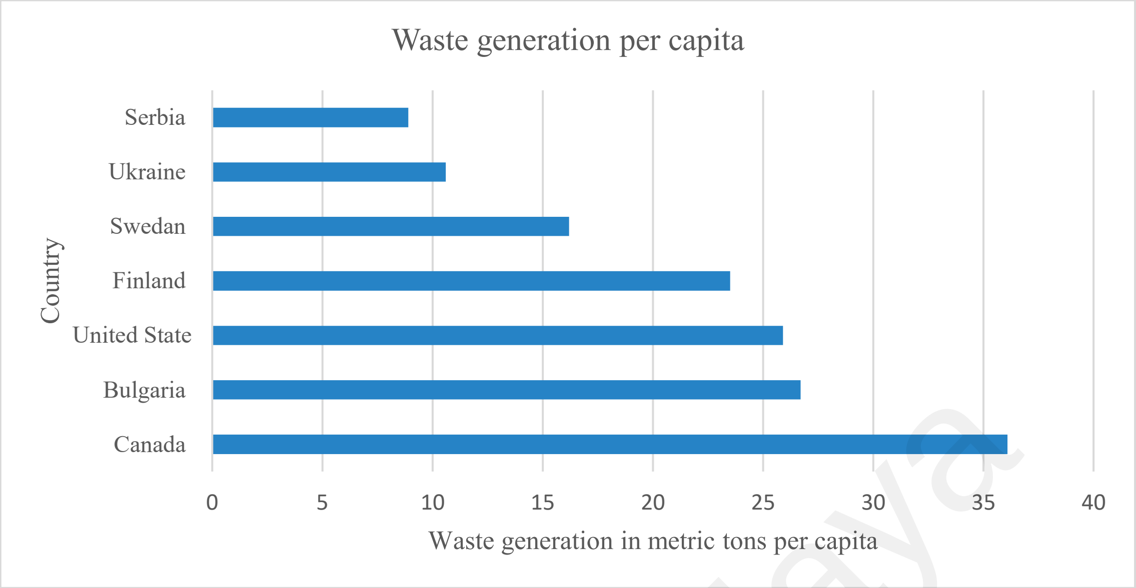


Figure 2.1 : Waste generation per capita of largest waste producing countries

MSW refers to the majority of non-hazardous solid waste collected and transported to a processing or disposal facility on a regular basis by municipality. Municipal solid waste includes food waste, vegetables, paper, plastic, plastic bottles, newspapers, glass bottles, aluminium foil, and wood pieces. It's estimated that the average daily production of MSW in Australia, Japan, Hong Kong, and Singapore is between 1.1 and 5.0 kg (Republic, 2021). Middle-income countries like Indonesia, Malaysia and Thailand produce between 0.52 and 1.0 kg/capita per day, according to the United Nations. Low-income countries that produce between 0.4 and 0.89 kg/capita/day waste MSW include Bangladesh, India, Vietnam, and Myanmar. The statistic shows that approximately 3.4 billion metric tons of MSW will be generated around the world in 2050. As can be seen in the Figure 2.2, East Asia and Pacific region is generating most of the world's waste, at 23 %, and the Middle East and North Africa region is producing the least in absolute terms, at 6 %.

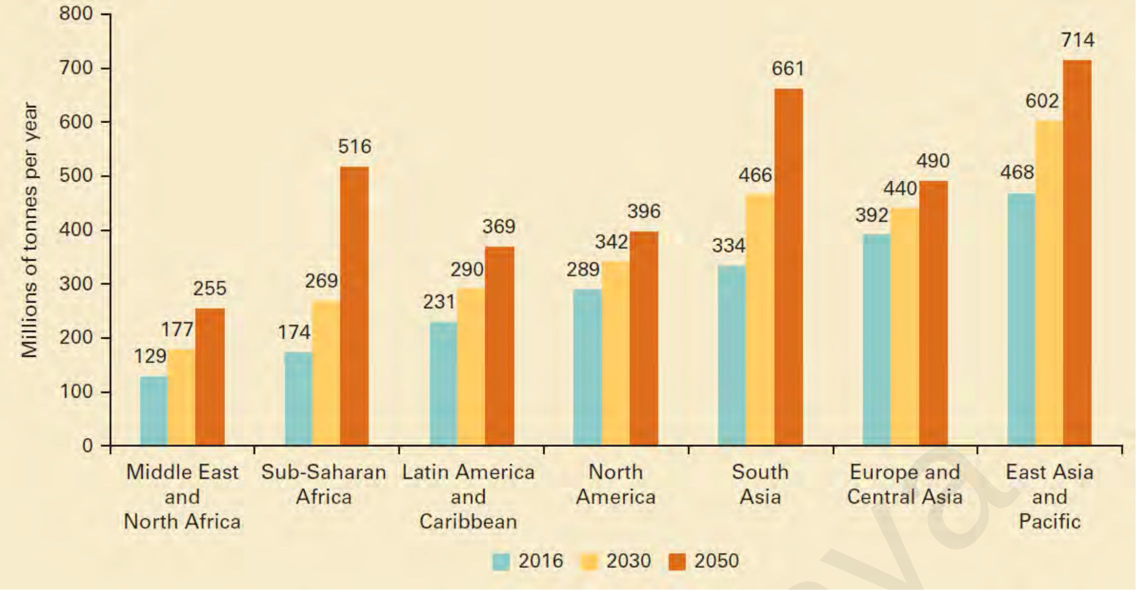


Figure 2. 2 : Projected waste generation, by region (millions of tons/year) (Republic, 2021

Environmental Protection Agency (EPA) established that hazardous waste exhibit one or more of the following four characteristics; ignitability, corrosivity, reactivity or toxicity. The hazardous waste identification process is illustrated in the Figure 2.3. When compared to non-hazardous waste, the generation and management of hazardous waste can contaminate land, air, and water, as well as have a detrimental impact on human health and the environment. Hazardous waste has been distinguished from municipal wastes and non-hazardous industrial wastes. According to Eurostat (2019), the amount of hazardous waste in the European Union increased by 4.9 percent between 2010 and 2016. Chemical wastes account up most of the hazardous waste (46.3%), followed by discarded equipment (29.9%) and mineral wastes (19.1%). Industrial waste is classified into nonhazardous and hazardous materials. In 2011 the global annual amount of industrial waste was estimated to be approximately 9.1 billion tons.

On the other hand, the quantity of clinical waste generated in 2020 rose 18.1 per cent or 39.9 thousand metric tonnes as compared to 33.8 thousand metric tonnes in 2019 in Malaysia. This increase was attributed to the used of personal protective equipment

(PPE) and COVID-19 test equipment in handling of COVID -19 patients in health facilities and quarantine centers. Selangor (9.7 thousand metric tonnes), Sarawak (4.1 thousand metric tonnes) and W.P. Kuala Lumpur (4.1 thousand metric tonnes) have recorded the highest amount of clinical waste. In addition, quantity of scheduled waste generated by industries recorded 7,185.2 thousand metric tonnes in 2020, an increase of 79.0 per cent compared to 4,013.2 thousand metric tonnes reported in 2019. This was contributed by power plant and water treatment plant industries which is categorised as essential services. In terms of states, Selangor contributed the highest amount of scheduled waste at 28.5 % followed by Johor (16.8%) and Negeri Sembilan (16.2%).

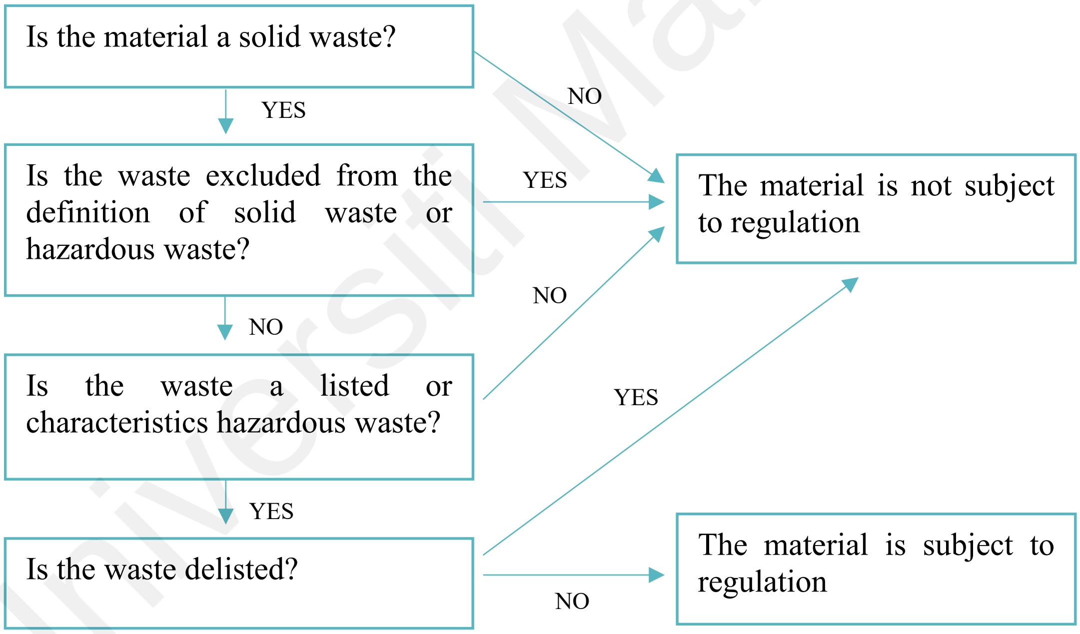


Figure 2. 3 : Hazardous waste identification process

It should be noted that the public funds allocated to solid waste management are insufficient, making even the management of small amounts of waste a significant challenge. At its core, the challenge is rooted in organizational structure and resource mismanagement.

2.2. Waste Management in Malaysia

In Malaysia, waste is classified as scheduled and non-scheduled waste. Scheduled waste is defined as waste that possesses hazardous characteristics such as ignitability, corrosivity, reactivity, or toxicity and poses a risk to public health or the environment. There are 77 types of scheduled wastes listed in the First Schedule of Environmental Quality (Scheduled Wastes) Regulations 2005 for waste management. Table 2.1 shows the 77 categories of first scheduled waste in the five grouping. Non-scheduled waste does not exhibit significant toxic properties, and thus is not classified as hazardous waste at the international level. Non-schedule wastes are any materials that do not fall into one of the 77 categories listed in Table 2.1 and Environmental Quality Act 1974 (Act 127), sewage as defined in the Water Services Industry Act 2006 (Act 655) or radioactive waste as defined in the Atomic Energy Licensing Act 1984 (Act 304). Non-schedule waste or municipal solid waste (MSW) can be divided into recycle waste including paper, carton boxes, wires/cables, plastic bottles, water drums, ink cartridge and metals and non-recyclable waste such as food waste. 'Controlled Solid Waste' including household solid waste, imported solid waste, commercial solid waste, institutional solid waste, construction solid waste, industrial solid waste, and public solid waste.

Table 2.1: 77 categories of hazardous waste

Code of Waste	Description
W1: Metal and metal-bearing wastes	
SW 101	Waste containing arsenic or its compound
SW 102	Waste of lead acid batteries in whole or crushed form
SW 103	Waste of batteries containing cadmium and nickel or mercury or lithium
SW 104	Dust, slag, dross, or ash containing arsenic, mercury, lead, cadmium, chromium, nickel, copper, vanadium, beryllium, antimony, tellurium, thallium or selenium excluding slag from iron and steel factory
SW 105	Galvanic sludge
SW 106	Residues from recovery of acid pickling liquor
SW 107	Slags from copper processing for further processing or refining containing arsenic, lead, or cadmium
SW 108	Leaching residues from zinc processing in dust and sludge form
SW 109	Waste containing mercury or its compound
SW 110	Waste from electrical and electronic assemblies containing components such as accumulators, mercury-switches, glass from cathode-ray tubes and other activated glass or polychlorinated biphenyl-capacitors, or contaminated with cadmium, mercury, lead, nickel, chromium, copper, lithium, silver, manganese, or polychlorinated biphenyl
SW 2: Wastes containing principally inorganic constituents which may contain metals and organic materials	
SW 201	Asbestos wastes in sludge dust or fiber forms
SW 202	Waste catalysts
SW 203	Immobilized scheduled wastes including chemically fixed, encapsulated, solidified, or stabilized sludge
SW 204	Sludge containing one or several metals including chromium, copper, nickel, zinc, lead, cadmium, aluminum, tin, vanadium, and beryllium
SW 205	Waste gypsum arising from chemical industry or power plant
SW 206	Spent inorganic acids

Table 2.1 (continued)

Code of Waste	**Description**
SW 207	Sludge containing fluoride
SW 301	Spent organic acids with pH less or equal to 2 which are corrosive or hazardous
SW 302	Flux waste containing mixture of organic acids, solvents, or compounds of ammonium chloride
SW 303	Adhesive or glue waste containing organic solvents excluding solid polymeric materials
SW 304	Press cake from pretreatment of glycerol soap lye
SW 305	Spent lubricating oil
SW 306	Spent hydraulic oil
SW 307	Spent mineral oil–water emulsion
SW 308	Oil tanker sludge
SW 309	Oil–water mixture such as ballast water
SW 310	Sludge from mineral oil storage tank
SW 311	Waste oil or oily sludge
SW 312	Oily residue from automotive workshop, service station, oil, or grease interceptor
SW 313	Oil contaminated earth from re-refining of used lubricating oil
SW 314	Oil or sludge from oil refinery plant maintenance operation
SW 315	Tar or tarry residues from oil refinery or petrochemical plant
SW 316	Acid sludge
SW 317	Spent organometallic compounds including tetraethyl lead, tetramethyl lead, and organotin compounds
SW 318	Waste, substances, and articles containing or contaminated with polychlorinated biphenyls (PCB) or polychlorinated triphenyls (PCT)
SW 319	Waste of phenols or phenol compounds including chlorophenol in the form of liquids or sludge
SW 320	Waste containing formaldehyde
SW 321	Rubber or latex wastes or sludge containing organic solvents or heavy metals

Table 2.1 (continued)

Code of Waste	Description
SW 322	Waste of non-halogenated organic solvents
SW 323	Waste of halogenated organic solvents
SW 324	Waste of halogenated or un-halogenated non-aqueous distillation residues arising from organic solvents recovery process
SW 325	Uncured resin waste containing organic solvents or heavy metals including epoxy resin and phenolic resin
SW 326	Waste of organic phosphorus compound
SW 327	Waste of thermal fluids (heat transfer) such as ethylene glycol
SW 316	Acid sludge
SW 317	Spent organometallic compounds including tetraethyl lead, tetramethyl lead, and organotin compounds
SW 318	Waste, substances, and articles containing or contaminated with polychlorinated biphenyls (PCB) or polychlorinated triphenyls (PCT)
SW 319	Waste of phenols or phenol compounds including chlorophenol in the form of liquids or sludge
SW 320	Waste containing formaldehyde
SW 321	Rubber or latex wastes or sludge containing organic solvents or heavy metals
SW 322	Waste of non-halogenated organic solvents
SW 323	Waste of halogenated organic solvents
SW401	Spent alkalis containing heavy metals
SW402	Spent alkalis with pH more or equal to 11.5 which are corrosive or hazardous
SW403	Discarded drugs containing psychotropic substances or containing substances that are toxic, harmful, carcinogenic, mutagenic, or teratogenic
SW404	Pathogenic wastes, clinical wastes, or quarantined materials
SW405	Waste arising from the preparation and production of pharmaceutical product
SW406	Clinker, slag, and ashes from scheduled wastes incinerator
SW407	Waste containing dioxins or furans

Table 2.1 (continued)

Code of Waste	Description
SW408	Contaminated soil, debris, or matter resulting from cleaning-up of a spill of chemical, mineral oil, or scheduled wastes
SW410	Rags, plastics, papers, or filters contaminated with scheduled wastes
SW411	Spent activated carbon excluding carbon from the treatment of potable water and processes of the food industry and vitamin production
SW412	Sludge containing cyanide
SW413	Spent salt containing cyanide
SW414	Spent aqueous alkaline solution containing cyanide
SW415	Spent quenching oils containing cyanides
SW416	Sludge of inks, paints, pigments, lacquer, dye, or varnish
SW417	Waste of inks, paints, pigments, lacquer, dye, or varnish
SW418	Discarded or off-specification inks, paints, pigments, lacquer, dye, or varnish products containing organic solvent
SW419	Spent di-isocyanates and residues of isocyanate compounds excluding solid polymeric material from foam manufacturing process
SW420	Leachate from scheduled waste landfill
SW421	A mixture of scheduled wastes
SW422	A mixture of scheduled and non-scheduled wastes
SW423	Spent processing solution, discarded photographic chemicals, or discarded photographic wastes
SW424	Spent oxidizing agent
SW425	Wastes from the production, formulation, trade, or use of pesticides, herbicides, or biocides
SW426	Off-specification products from the production, formulation, trade, or use of pesticides, herbicides, or biocides
SW427	Mineral sludge including calcium hydroxide sludge, phosphate sludge, calcium sulfite sludge, and carbonates sludge

Each day, over 30,000 tonnes of solid waste are disposed of in 166 landfills compared to 19,000 tonnes per day in 2005, with a recycling rate of 5% (Chu, 2019). Table 2.2 summarises the typical municipal solid waste generated in Malaysia. The main components of Malaysian MSW are food, paper and plastic, which make up almost 80% of the waste by weight. The average moisture content of the MSW is about 55%, which makes incineration a challenging task (Johari, Ahmed, Hashim, Alkali, & Ramli, 2012; Kathirvale, Muhd Yunus, Sopian, & Samsuddin, 2004; Saeed, Hassan, & Mujeebu, 2009). The solid waste generally has a bulk density above 200 kg/m^3 (Manaf, Samah, & Zukki, 2009).

Although disposal methods such as composting and recycling introduced in the past decades, the use of landfills remains the most widely accepted and utilised method for waste disposal in developing countries, such as Malaysia. In terms of cost savings and simplicity of operation, it is preferred compared to other methods. One of the challenges with landfilling is that leachate from the landfill can pollute the environment. Leachate is wastewater with high pH, high COD, high BOD, high salt, and toxicity (Kamaruddin et al., 2017). According to the National Solid Waste Management Policy 2016, a national recycling rate of 22.0 percent is to be achieved by 2020. As a result, Malaysia's recycling rate in 2019 was 28.1% higher than the set target of 20%. However, South Korea and Singapore recorded recycling rates of 53.7 percent and 34.0 percent, respectively, in 2019.

Since the 21st century, proper management of a nation's MSW has become and continues to be a high priority area for every country's government. Stemming from the current problems of disposing MSW, a holistic concept of integrated solid waste management has become a necessity in planning for the future. This includes source reduction of waste before entering the waste stream, recovery of generated waste for recycling and composting and environmentally sound disposal through combustion facilities and sanitary landfills that comply with best management practices.

Table 2.2: Typical MSW characterization in Malaysia (Johari et al., 2012)

Source	Residential Income (%)			Percentage (%)		
	High	**Medium**	**Low**	**Commercial**	**Institutional**	**Avg.**
Food/organic	30.8	38.4	54.0	41.4	22.3	37.4
Mix paper	9.7	7.2	6.3	8.9	11.2	8.7
Newsprint	6.0	7.7	3.7	7.1	4.3	5.7
High grade paper	-	1.0	-	0.3	-	0.6
Corrugated paper	1.3	1.7	1.5	2.1	1.1	1.5
Plastic (rigid)	3.8	3.5	1.9	3.5	3.5	3.2
Plastic (film)	21.6	14.7	8.9	12.7	11.8	13.9
Plastic (foam)	0.7	1.7	0.8	0.8	4.1	1.6
Pampers	6.4	7.5	5.8	3.8	1.6	5.0
Textile	1.4	3.5	5.4	1.9	4.6	3.4
Rubber/leather	0.4	1.7	1.4	0.8	2.0	1.3
Wood	5.8	1.3	0.8	0.9	9.8	3.7
Yard	6.1	1.1	2.0	5.7	0.8	3.1
Glass (clear)	1.5	2.0	1.2	2.9	0.2	1.6
Glass (colored)	1.1	2.0	0.1	1.8	0.2	1.0
Ferrous	1.9	3.0	2.2	2.4	3.7	2.6
Non-ferrous	0.1	0	0.1	0.5	1.5	0.4
Aluminium	0.3	0.1	0.3	0.2	0.1	0.2
Batteries/ hazards	0.2	0.1	-	0.2	0.1	0.1
Fine	-	0.7	2.6	0	0.3	0.9
Other organic	0	0	-	1.2	1	0.5
Other inorganic	-	0.2	0.2	-	8.0	2.8
Others	-	-	-	-	6.9	6.9

On the other hand, scheduled waste or hazardous waste also one of the noticeable concern since 1970. In 2008, the hazardous waste generated was 1.3 million tons [28, 29], while in 2011, it grew to 1.6 million tons. However the scheduled wastes generated in 2019 was 4.0 million tonnes, it is increased by 7.5 % compared to 2018. The power plant, metal refinery, chemical industry and electrical & electronics contributed 57.1 per cent (2.3 million tonnes) to the total scheduled wastes. The amount of clinical wastes in 2019 was 33.8 thousand tonnes, an increase of 7.5 per cent as compared to 31.4 thousand tonnes in the previous year. Several states, including Selangor (7,300 tonnes), W.P. Kuala Lumpur (3,800 tonnes), and Sarawak (3,700 tonnes), accounted for the largest amount of schedule waste generation.

The hazardous wastes listed in Table 2.1 are generated from a variety of sources, including industrial, agricultural, the health sectors, and households. The waste generation has increased in the past years, and it is expected to continue to rise. Clinical wastes generated in the country increased by 20.0 % during the COVID-19 pandemic, and it is expected to rise in the coming years. In achieving more integrated waste management solutions, the Government had further extended the tax incentive for Green Technology through the Budget 2021. The incentive aims to encourage firms to revise their approach by incorporating a combination of waste management techniques including collection, storage, composting and disposal with other core recycling, recovery or waste treatment activities. These activities will strengthen the ecosystem of green technology in Malaysia and enhance firms' operations to include a more holistic approach to waste management.

2.3. Current Waste Management Practices

The waste management is varying from one country to another. However, the statistics indicates that the gross domestic product (GDP) per capita increases with per capita waste. The following section discusses the various waste treatment and disposal systems that are now in use around the world. Waste management in much of the country have been redefined in the last 30 years because of major challenges and public concern. Because no single waste management strategy is adequate for all types of waste, numerous management techniques are used, ranging from the most environmentally sound to the least environmentally sound. Figure 2.4 shows the traditional waste management hierarchy implemented in most of the countries which involves , reduction, reuse, recovery, treatment and disposal .

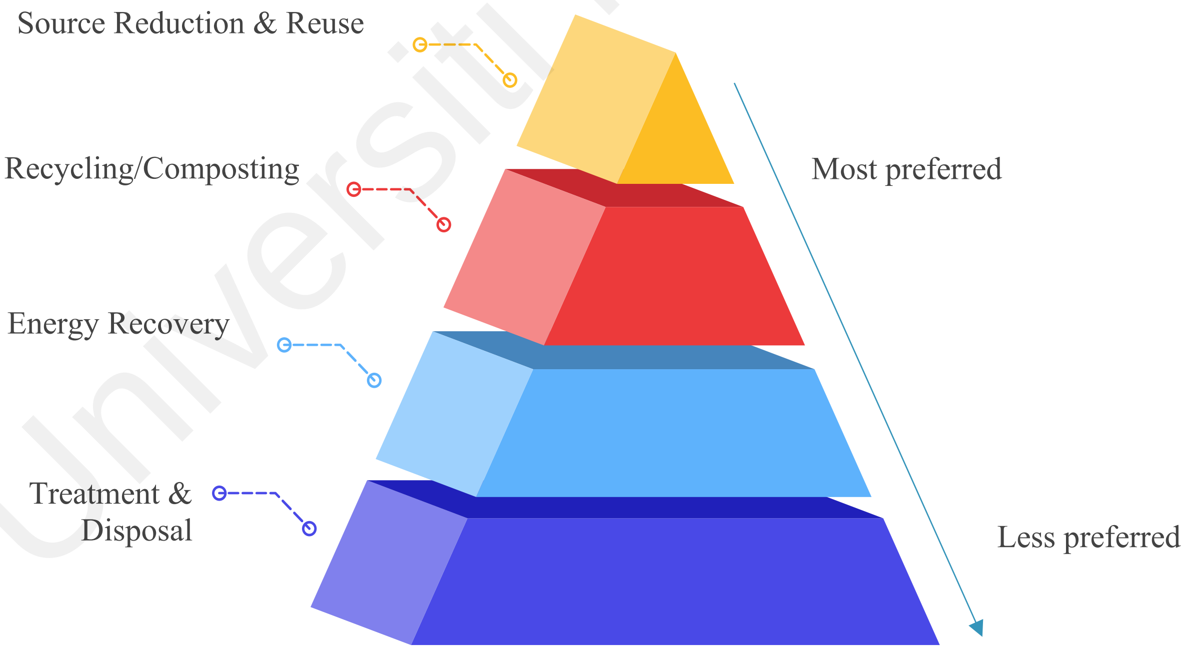


Figure 2.4 : Hierarchy of Waste Management

2.3.1. Municipal and Hazardous Waste Incineration

Incineration is a thermal waste treatment method that uses controlled combustion or calcination to reduce waste volume and recover energy at high temperatures (Moharir, Gautam, & Kumar, 2019). Incineration is the most popular process waste treatment method used to reduce the volume of municipal solid waste, while reducing landfilling cost since 1880s. Hazardous and non-hazardous solid or liquid waste are being incinerated to destroy organic and inorganic compounds to convert them into ash, heat and combustion gases. Combusting waste produces heat, while inorganic waste leads to the formation of ash(Ghosh, Sengupta, Singh, & Sahay, 2020). Industrial furnaces and boilers are commonly used for incineration of waste. Industrial furnace uses thermal energy for hazardous waste treatment to recover energy from waste. Furnace is being used in the cement kilns, lime kilns, and phosphate kilns. Boilers, on the other hand, use controlled flame combustion to recover thermal energy as steam.

In Malaysia, incineration plants are built to cater to all type of non-hazardous and hazardous organic waste, including toxic, hazardous, clinical and pathological waste in all forms, solids, sludge and liquids all organic waste that requires thermal treatment to achieve maximum destruction efficiency. A rotary kiln as the primary combustion chamber with a temperature of up to 1000°C and secondary combustion chamber operating at above 1000°C to ensure the highest possible destruction efficiency, followed by heat recovery system and finally an extensive multi-stage flue-gas treatment system. Designed with multiple feed streams, dual combustion chambers, rapid cooling, dry and wet scrubbing systems, the plant is designed to achieve 99.99% destruction and flue-gas removal efficiency. Emissions from this plant meet all Malaysian Environmental standards. The incineration process is being monitored by Continuous Emissions Systems (CEMS) to ensure the compliance with Department of Environment, Malaysia (DOE) license condition. Fully computerised and equipped with continuous monitoring systems, the incineration plant represents the latest standard in rotary kiln incineration technology. In 2011, about 12% of the total MSW generated (17.9% of the MSW disposed) was converted through combustion with energy recovery. However, incineration is generally regarded as unfavourable from an environmental standpoint, as it has been reported that 1 kg of solid waste can produce 0.51 kg of CO_2 equivalent emissions when incinerated (Wang and Geng, 2015).

Both developing and developed countries face difficulties in treating solid waste in an environmentally sound way. Dioxins, furans, nitrous oxides, chloric acid, sulphur oxide and other gases are emitted when solid waste is burned in incinerators. The harmful chemicals and gases emitted from incinerators are restricted as per the Clean Air Act of 1970. Many studies have been conducted to develop and improve the operation technology to overcome the dioxin and other poisonous gas emission issues. Japan is a a leader of construction and management of incinerators. Japan managed to developed a newer incineration technology enable electric generation from recovered heat waste and reduce the emission of greenhouse emission. Besides the new technology also generates clean electricity compared to the conventional method. Singapore, Thailand Taiwan are among the countries that using incineration technology from Japan.

2.3.2. Waste Landfilling

Landfilling is the preferred waste disposal technology in most of the countries. Wastes that cannot be reduced, reused, recycled, or recovered are dumped in landfills. Landfills are divided into landfills for hazardous waste, non-hazardous waste and inert waste. Agricultural waste, solid waste from markets, hotels, households, public places, schools, and malls, and biodegradable industrial and construction wastes are examples of waste that are always disposed in landfills. General waste and hazardous waste are using different capping systems. HW undergoes physical, chemical treatment before they are landfilled. Some of the important considerations for sustainable landfilling are landfill liners, soil cover thickness, leachate collection, landfill gas recovery, and flaring facilities (Nanda & Berruti, 2021).

Waste management facilities should be kept far away from house development project as well as catchment areas and marine or coastal reserves. Landfills should be designed and operated in such a way that they can effectively manage pollutants such as landfill gas, leachate, and rainwater. The statistics, shows that around 60% of waste generated in Malaysia is disposed of in landfills, where more than half of the existing landfills have reached their maximum capacity. Recycling, incineration, and composting are typical ways in Malaysia; if waste cannot be recycled, landfilling is the final option. According to Solid Waste Management and Public Cleansing Corporation (SWCorp Malaysia), Malaysia has 14 sanitary landfills, 161 of which are still operational and 141 of which are closed.

In line with the EU's transition to a circular economy, the majority of the country has agreed to place restrictions on the landfilling of waste that is eligible for recycling or energy recovery, as well as limiting municipal waste landfilling. The world need more landfills due to the increase of significant urbanization and population rate. Plastics are one of the most significant problems that arise as a result of urbanisation and must be managed in landfills.

2.3.3. Recycling

Implementing a comprehensive waste management strategy is exceedingly difficult. Waste management methods such as reuse and recycling, as well as a thorough understanding of the solid waste and HW generation process, can help to reduce waste disposal more efficiently. Waste minimization or reduction requires detail knowledge about all the production process. The shift from tradition approaches of cradle to grave need to be evaluated and replaced with cradle to cradle approach to solve the increasing generation of waste. The waste could also be minimized through a comprehensive 7Rs initiative, i.e Rethink, Repair, Reduce, Recover, Reuse , Recycle and Refurbish.

2.3.4. Biomass Utilization Technology

Waste generated in cities and villages includes combustible wastes with low and high moisture content waste. Waste with high moisture content such as food production waste, kitchen waste, manure, sewage sludge, biomass and other organic sludge will generate methane gas and hydrogen sulphide when buried without treatment. The sewage sludge contains proximately 80% organic matter and the 20% of inorganic matter. The inorganic matter can be recycled as material for cement and bricks. While Organic matter could be recycled as fertilizer, sewage gas and fuel. The Fossil fuel is can be replaced by fuel obtained from sewage sludges to reduce CO_2 emissions. Besides, there is a high ratio of organic waste in waste products, and it is desirable to make effective use of organic waste generated from paper and palm oil industries.

Composting and methane fermentation can be used for recycling food waste. Composting is the commonly used biological process to convert solid waste with the help of microbes. Reduction in disposed food waste helps in decreasing the waste disposal cost and greenhouse gas emissions. On the other hand, the waste form paper or wood manufacturing premises can be used for boilers. Moisture content and shape differ depending on where the waste is generated, and it is burned in several types of incinerators. Palm waste is a valuable boiler fuel, and steam generated from boilers is used for oil extraction process or electrical power generation.

2.4. Waste to Energy Concept

The concept of waste to energy (WtE) is very useful in utilizing waste as a source of energy. Waste that cannot be recycled or reused is allegedly exclusively intended for WtE. The conversion of non-recyclable waste materials into heat, power, or fuel by a number of processes such as combustion, gasification, pyrolysis, anaerobic digestion and is known as energy recovery. Waste to energy is a well-known non-hazardous waste management strategy that minimizes carbon emissions by offsetting the need for electricity from fossil sources and reducing methane formation in landfills.

The organic compound (both biodegradable and non-biodegradable) from the Municipal Solid Waste (MSW) can be recovered through suitable waste processing and treatment. Thermo-chemical and biochemical conversion are two commonly used method for the energy recovery. Thermal-chemical conversion is a method of decomposing organic materials to generate heat, fuel, or gas. It is particularly useful for waste with a high percentage of organic non-biodegradable matter and low moisture content. The most common thermo-chemical conversion technologies are pyrolysis, and gasification. The thermochemical conversion techniques being used currently for biofuel production were adapted from fossil fuel industries since 1970s. Aside from the complex composition of both biomass and its degradation products, research of biomass conversion processes for biofuel production is currently insufficient. As the temperature rises, the biomass first destructs, then degrades to condensable vapors, and eventually decomposes to gaseous molecules in the thermochemical conversion process (Zhang & Zhang, 2019). On the other hand, bio-chemical conversion based on enzymatic decomposition of organic matter by microbial action to produce methane gas or alcohol.

2.5. Refuse Derived Fuel from Waste

Refuse Derived Fuel from waste (RDF) refers to an unlimited range of solid, liquid and gaseous waste materials from household, forestry, agriculture and industry, which have a certain calorific value (Buekens, 2013; Fodor & Klemeš, 2012; KlemeŠ & Varbanov, 2006). Generally, sewage sludge, waste wood, fractions of household and commercial waste, shredder lightweight fractions, scrap tyres, food by-products, waste oil and used solvents can be considered as RDF.

Historically, in 19th century RDF was initially used in producing steam from MSW in England. The technology was then adopted in the United States, Germany, and Japan. Furthermore, in the 1890's, MSW were used as raw materials to produce RDF, which was burned as a fuel in generating electricity. In 1975, the first full-scale energy recovery from waste facility was operated, where RDF produced was sent to a local power plant for supplemental fuel. In Malaysia the first Waste to Energy (WtE) facility located in Kajang municipality. The RDF power plant is situated on a 28-acre property and receives 700 tonnes of unsegregated MSW every day, for which a tipping fee of RM 46 per tonne (US$13) is imposed. The waste consists of a large percentage of organics waste with a high moisture content, 15 % of plastics, and other items. The RDF plant is designed to remove recyclable plastics and metals while also producing RDF possible energy recovery. The RDF plant runs on the electricity generated, with the rest sold to the national power grid.

ASTM standard (2006) defined RDF as a shredded fuel derived from MSW, which metal, glass and other inorganic materials have been removed and has particle size 95 % wt. passes through a 2 inch square mesh screen. According to ASTM standards E856-83 (2006) (ASTM, 2004), RDF can be classified into 7 categories and the resultant fuel descriptions are summarized as below:

(1) RDF-1: Wastes used in as discarded form, namely Raw RDF. This waste go through minimal processing to remove oversize bulky waste.
(2) RDF-2: Wastes processed to coarse particle size with or without ferrous metal separation such that 95 % wt. passes through a 6-inch square mesh screen, namely Coarse RDF.
(3) RDF-3: Shredded fuel derived from wastes processed to separate glass, metal and other inorganic materials; particle size of this material is such that 95 % wt. passes 2 in square mesh screen, namely Fluff RDF.
(4) RDF-4: Combustible wastes processed into powder form, such that 95% wt. passes through a 10 mesh screen (0.035 inch square), namely Powder RDF.
(5) RDF-5: Combustible wastes densified (compressed) into the form of pellets, slugs, cubettes, briquettes or similar form, namely Densified RDF.
(6) RDF-6: Combustible wastes processed into liquid fuels, namely RDF slurry.
(7) RDF-7: Combustible wastes processed into gaseous fuels, namely RDF syngas.

RDF covers a wide range of waste materials, which are processed to fulfill the guidelines, regulatory, or industry specifications mainly to achieve a high calorific value. RDF mainly consist of residues from MSW, industrial waste, sewage sludge, and biomass waste, etc. In the RDF plants, various types of waste received are segregated where non-recyclable or non-combustible materials are removed, while the remainders are processed into a uniform fuel, which has a higher calorific value than the MSW. Currently, RDF is used as fuel/co-fuel in cement kilns, lime kilns, coal-fired power plants, industrial boilers and gasification and combustion based combined heat and power plants to produce energy (power and heat).

2.6. Characterization of Refuse Derived Fuel

The composition of RDF varies according to the sources of waste materials, collection system and treatment applied. The main characteristics of RDF as an alternative fuel are the calorific value, moisture content, ash content, heavy metals, sulfur and chlorine content. Table 2.3 shows the composition of various materials of typical standard RDF (Hasibul, Quazi, & Hassan, 2015). It should be noted that the calorific value and the properties of RDF are greatly influenced by the source. Table 2.4 shows characterization of RDF from different sources.

Table 2.3: Waste Composition of standard RDF

Components	**Percentage (Weight)**
Plastic	60%
Paper	10%
Wood	5%
Textiles	10%
Others	15%

Table 2.4 : Properties of RDF

Source of RDF from waste type	Calorific value (MJ/kg)	Ash content (%wt.)	Chlorine content (% wt.)	Sulfur content (% wt.)	Moisture content (% wt.)
Household	10 - 12	15 - 20	0.3 - 1	0.1 – 0.2	25 - 30
Commercial	14 - 16	5 - 7	< 0.1	< 0.1	10 - 20
Industrial	18 - 21	10 - 15	-	0.2 - 1	3 - 10

2.7. Utilization of Waste for the Development of Refuse Derived Fuel

A wide range of industrial wastes are used as an alternative fuel. The wastes include plastics and papers from commercial and industrial activities, used tyres, biomass waste, waste textiles, etc. Industrial wastes used as alternative fuels need to be treated to meet industrial specifications. For example, homogenisation to provide a consistent calorific value and the limiting of compounds such as chlorine or phosphorous for clinker production. For example, industrial sludge, spent solvent or waste oil are mixed with sawdust before being supplied in cement kilns, waste tyres are shredded, sewage sludge is dried, etc. RDF generated from commercial and industrial wastes, such as rejected papers from paper manufacturing or packaging waste may require size reduction or pre-screening, but usually did not require advanced physical processing to reduce the contaminants.

2.7.1. Rubber/ Latex Waste

Malaysia is the one of the world's major producers of rubber and latex. The waste and sludge generated from latex production process can be utilized as RDF due to their high calorific values. Currently, most of the waste being produced by Malaysian rubber industries are being dumped at the landfill.

2.7.2. Ink, Pigment, Paint and Dye Waste

Paint, auto manufacturing and textile industries are generating around 19 000 MT/year in Malaysia. These types of waste are being landfilled and incinerated. Basically, the wastes from these industries is high in organic carbons and solvents, which can contribute to higher calorific value.

2.7.3. Used Tyres

Used tyres are waste from automobile industry and generally disposed oin landfills or stockpiled. In the 80's, derived fuels from used tyres became very popular to the cement industry, mainly due to its high calorific value of 7,800 – 8,600 kcal/kg as compared to coal of 5,500 – 7,200 kcal/kg (Gray, 2004). Used tyres can also be used as a replacement of raw materials containing iron, where there is no significant differences in the chemical composition of the clinker manufactured by used tyres as opposed to fossil fuel. Though the use of used tyres in cement kilns reduces resource consumption, it was intensively studied for their environmental impacts, mainly SO_2 and NO_x emissions.

2.7.4. Spent Pot Liner

Spent pot liner (SPL) are solid waste produced from aluminium industry during the manufacture of aluminium metal in electrolytic cells. The lining of the cell is comprised of carbon, which is backed by insulation and contained within a steel container called a pot shell. The carbon portion of the lining serves as the cathode for the electrolysis process. After a certain period the cell lining become impregnated with fluoride-containing salts. Then the cathode lining material is removed from the pot shell by mechanized digging equipment. This spent cathodic material is referred as SPL. The life cycle of a cathode typically varies from about 3 - 10 years. The heating value of SPL is

25.2 MJ/kg, which is almost equal to bituminous coal. The total SPL generation in the world was about 800,000 tons in the year 2003, which implies the availability of SPL as alternative fuel. At 20°C, the cyanide content of SPL is 0.033% and a test study showed that almost 99.9% of the cyanide is destroyed when it is used as alternative fuel in a cement kiln. However, SPL has high fluorine content.

2.7.5. Plastic Waste

Plastic waste is considered as one of the most readily available source for alternative fuel in cement industry due to their high calorific value of 29 - 40 MJ/kg. Plastic wastes are available as municipal waste as well as industrial waste. However, the only concern of using plastic waste is the chlorine content. The accepted particle size for the incineration process is 10×10×10 cm and a shredder is needed when larger parts are charged in the kiln. Isolation of materials from plastic waste and retrofitting requires additional capital and labour costs. Use of chlorinated plastics can affect clinker quality. Emission of dioxins and furans can be increased by the presence of chlorine under specific conditions. The NO_X emission, while burning plastic waste, depends on the nitrogen content of the plastic and some other issue such as the flame temperature and air quantity.

2.7.6. Sewage Sludge

A large amount of sewage sludge is produced worldwide during wastewater treatment. Landfill, use in agriculture as organic fertiliser and soil conditioner are the main conventional methods of disposal, most of which are not environmentally friendly. The most common sewage sludge disposal alternative is to incinerate it in cement kiln and confine the ash in the clinker. Main advantage of using sewage sludge in cement kiln is the reduction of landfill, which may cause human health and environmental risks. The heating value of sewage sludge depends on the moister content and with 5% of moisture content it is 15.8 MJ/kg. The ash from the sludge substitute raw material in cement manufacturing hence reduces the production cost. NO_X emissions are reduced while using sewage sludge compared to the fossil fuels. Sewage sludge causes an increase in heavy metal emissions compared to fossil fuels. More intensive studies are needed to increase the reliability of these findings.

2.7.7. Solvent and Spent Oil

Spent lubricating oil can be found from any types of industries ranging from finishing industries to high technology manufacturing industries. Lubricating oils are used in variety capacities as a non-conductive lubricant. Because of the high calorific value, the spent lubricating oil can be used as RDF production feedstock. Solvent and spent oil from different industries generally have high calorific value and those can be used in cement kiln as alternative fuel with minimal processing cost. The maximum and minimum calorific values of solvent and spent oil were 29 MJ/kg and 36 MJ/kg, respectively and the variation occurred due to the ratio of different chemical in it. Most of the time, the cement plants are established in the vicinity of industrial area, which makes the solvent and spent oil a highly acquirable fuel in minimum transportation cost.

Storage is the major issue for solvent and spent oil as there is a possible chance of volatile organic compound (VOC) emission. Solvent and waste oil contain less minerals compared to cokes and coal hence a little additional raw meal is needed to ensure the quality of the cement. There is a reduction of nitrogen oxides when using spent solvents as compared to fossil fuels. CO_2 emission was reduced while solvents and paint sludge were used as alternative fuel.

2.7.8. Other wastes

Apart from the above-mentioned industrial wastes, there are varieties of other alternative fuel, which can be found in literature. Amongst them carpet waste, oil-soaked rags, automobile shredded residue, fluff, textile waste, paper residue, packing boxes are few to name. Unfortunately, not much information regarding their uses and impact are available and there is a need for more research to justify their practicality.

2.8. Challenges of Typical Refuse Derived Fuel

RDF has a high heating value due to its production proces, which reduce its size, make it drier and separates it from unwanted waste materials (Chyang et al., 2010). RDF is cheaper compared to fossil fuel, which makes it attractive to industries (Ariyaratne et al., 2014). Besides, it is readily combustible or can be mixed with other fuels. It can also be stored under room temperature for 6 to 12 months without decaying (Chen et al., 2011). RDF is a heterogeneous fuel processed from non-recyclable materials starting from pre-sorting, shredding, screening separation by cyclone or magnetic separator, scrubbing, granulation and fry-drying process which can reduce the sludge moisture from 80% to lower than 5% and increasing the calorific value of the product (Chang et al., 2013; Bosmans et al., 2014; Ariyaratne et al., 2012). Microwave plasma and torch technology are previously used to remove the moisture content of the waste materials but they require high-energy consumption. Therefore, other methods have been developed by combining organic sludge with sawdust (Chen et al., 2011). Binding agents such as oily or organic wastes, molasses fibrous, pitch, bitumen, starch, and dolomite can be added into waste to produce RDF briquette with high physical strength (Chiemchaisri et al., 2010).

Waste contains both organic and inorganic material (Ollila et al. 2006). During incineration, organic material is combusted while inorganic materials forms ash or volatile matter, which is a challenge of using RDF. For example, RDF from the current production process contains materials that limit its utilization in the firing system. Besides, incombustible materials such as ceramic and metal in RDF can damage conveying systems or contaminate the end products while ash composition potentially causes lagging and corrosion to the systems (Kruger et al., 2014; Wang et al., 2014). The current combustion technology has a low efficiency, approximately 20% of RDF combustion steam requires dioxins and furans treatment, resulting in high capital and operating cost. However, several technologies have been developed to overcome this issue such as gasification and use of syngas in the boiler that inherently reduce emission of both dioxins and furans (Dunnu et al., 2012; Gregorio & Zaccariello, 2012). The temperature of steam gasification has to be optimized to improve the selectivity of hydrogen and carbon monoxide and Dalai et al., (2009) suggested 725°C as the optimum temperature. Besides, fly ash can be of importance as it is commonly used as an additive in cement kiln industry (Tkaczewska et al., 2012). Even though the energy content in RDF is much lower compared to that of fossil fuel, the energy can be increased significantly by using catalysts, as shown in a study by Miskolczi, Buyong, Angyal, Williams, & Bartha (2010) who demonstrated that Nickel-molybdenum and Cobalt-Molybdenum catalysts could reduce contaminants.

2.9. Development of Refuse Derived Fuel

The process for producing RDF has two subsystems called front end and back end. The front end can also be considered as pre-processing subsystem and is intended to receive the MSW and separate it into combustible and non-combustible fractions. This is to produce the feedstock for the back-end system. The back-end system is where the conversion process occurs, which can either be thermal or biological system (Blanco, Wu, Onwudili, & Williams, 2012; Shrestha & Singh, 2012).

RDF production line consists of several unit operations in series in order to separate unwanted components and condition the combustible matter to obtain required RDF characteristics. General unit operations are screening, shredding, size reduction, classification, separation either metal, glass or wet organic materials, drying and densification. These unit operations can be arranged in different sequences depending on coming MSW composition and required RDF quality (Caputo & Pelagagge, 2002).

2.9.1. Manual Separation

In mixed waste, bulky materials received can be sorted and removed manually by workers before mechanical processing. Manual sorting also serves as recycling process for paper, glass or plastic containers and aluminium cans. Equipment involved in manual separation usually includes a sorting belt or table. Sorters are stationed on one or both sides of the belt or table to pick up the recycled materials. Design of manual separation requires good understanding of time and motion, waste composition and comfortable or safety operation of the sorters.

2.9.2. Size Reduction

Size reduction in solid waste management is similar to shredding and grinding. But shredding often refers to size reduction of the mixed wastes. Grinding is sometimes used for glass. Size reduction is an essential unit operation in mechanical processing of mixed wastes since it gives a certain degree of size uniformity. Shredding of mixed waste to the size of about 10 cm. is common in many waste-processing facilities. Sometimes, secondary or tertiary shredding to the size of smaller than 10 cm is required for production of RDF. There are many types of shredders as follows:

a) Hammer Mills

There are two types of hammer mills, horizontal and vertical rotors. The horizontal hammer mill is commonly used for mixed wastes. Its principal parts are rotor, hammer, and grates, frame and fly wheel. The objects will be fed into the opening of the machine to adjust the size. They interact with the hammers and each other until the size are small enough to pass through the grates.

b) Shear Shredder

This type of size reduction machine has high torque and low rpm. It consists of two horizontal cutting shafts that rotate in opposite directions. Due to its high torque and shearing action, this machine is commonly used for materials that are difficult to shred such as tire, aluminium and plastic. Energy consumption is an important parameter in designing size reduction equipment. The specific energy requirement for size reduction depends on the required product size, the less the size, the more the specific energy requirement.

2.9.3. Screening

The purpose of screening is for size separation. It divides the feedstock into at least two streams called oversize (retained on the screen) and undersize (passed through the screen) fractions. There are a few types of screens as follows:

a) Trommel Screen

Trommel is inclined downwardly, rotary, cylindrical screen. Its screening surface is either wire mesh or perforated plate. It can be use for mixed MSW/HW prior to size reduction called pre-trommeling or after shredding called post-trommeling. Trommel screen has been proven to be quite effective and efficient for processing mixed MSW and hence it is the commonly used type of screen.

b) Disc Screen

The predominant application of disc screen is for separation of inorganic fraction from RDF, from paper or from wood waste. A disc screen consists of evenly spaced shafts in horizontal plane fitted with discs. The openings between the discs allow the undersize to fall. All shafts rotate in the same direction and carry the wastes from one end to another end.

2.9.4. Air Classification

Air classification is a separation process by the differences in aerodynamic characteristics of waste. Aerodynamic characteristic of a particular material is a function of size, geometry, and density. The process consists of the interaction between moving stream of air, shredded wastes, and gravitational force. The fraction which is suspended in the air stream referred to light fraction and the settle materials are referred to heavy fraction. In air classification of shredded mixed waste, paper and plastic materials tend to be concentrated in the light fraction and metals, glasses are the main components of the heavy fraction.

2.9.5. Magnetic Separation

Magnetic separation is used to segregate ferrous metals from mixed waste. There are three configurations of magnetic separator namely magnetic head pulley, drum and magnetic belt. In terms of yield, the magnetic metal recovery per unit weight of total magnetic metal in mixed waste is about 80% for single stage of magnets. Higher rate of recovery can be achieved by using multiple stages magnetic separation. The percentage of recovery will be higher up to 85 - 90% when magnetic separator is used after air classifier. This is due to light contaminants such as paper and plastic, which interfere with magnetic separation process, have been removed.

2.9.6. Drying and Densification

Drying and densification are used in specific purposes such as RDF production and volume reduction of waste prior to landfill. The objective of drying is to improve the quality of RDF. Densification is used for production of densified-RDF by the way of briquetting, pelletizing, or cube formation.

2.10. Application of Refuse Derived Fuel

Currently, the targeted RDF users are energy-intensive industries such as cement, power generation either co-combustion or mono-combustion.

2.10.1. Cement Kiln

The cement industry's replacement of fossil fuel with "alternative" fuel entails minimising the usage of petroleum coke, the conventional fuel, and replacing it with waste or biomass. Industrial solid waste, MSW, RDF, tyres, waste oil and solved, plastics, textiles and paper waste, and biomass such as meat and bone meal, wood waste, recycled paper, agricultural waste such as rice husks, sawdust, sewage sludges, and biomass crops are examples of ‘alternative fuels' used by the cement industry. The cement factory is obligated to use waste and biomass as a fuel since it reduces greenhouse gas emissions and diverts waste from landfills.

In cement kilns, combustion takes place under very high flame temperatures about 1,450°C and relatively long residence times. Based on technical and environmental considerations, the analysis of burning RDF in a cement kiln shows that no special firing technology has to be installed except RDF handling system. However, there is an upper limit to the total fuel consumption (not more than 30%) for firing RDF in order that there is no increment in the emission levels of air pollutant such as acid gases, dioxins, furans, etc. There are 2 fuel-feeding points, namely pre-calciner and main burner.

a) Rotary Kiln

The calcinated material entering the kiln then undergoes a long heating process. The material temperature rises from 1,000°C to 1,450°C. Mineral matrixes of raw material are totally destroyed and cement minerals are formed at the sintering temperatures. A semi-product called clinker is formed. Coal and other alternative fuels are used as energy sources for the process. The ash from fuels is absorbed into the clinker matrix. The residual heat from the clinker leaving the kiln is recovered by a grate cooler to reduce the energy requirement.

b) Grate Cooler

The residual heat from the clinker leaving the kiln is recovered by a grate cooler (consisting of rows of grates). Cooling air is injected from the bottom of the grate, and is forced into the clinker, which is traveling slowly on the grate. The heated air is then recycled as secondary air for combustion in the kiln, or in the pre-calciner.

c) Finish Mill

The final process of cement making is called finish grinding. Clinker dosed with controlled amount of gypsum is fed into a finish mill. Typically, a finish mill is a horizontal steel tube filled with steel balls. As the tube rotates, the steel balls are lifted, tumble and crush the clinker into a super-fine powder. A high efficiency air separator controls the particle size. Other additives may be added during the finish grinding process to produce specially formulated cement. It has been proved that RDF and coal co-combustion in cement kiln has several advantages as follows:

(i) High temperature (1,800°C at main burner and 1,000°C at pre-calciner) and long residence time (5 - 6s at 1,800°C and 2 - 6s at > 800°C) yields complete combustion.
(ii) Self-cleaning process of acid gas by lime.
(iii)No ash since ash will be melts and becomes part of final product.

2.10.2. Power Plant

Co-firing waste derived fuels in coal-fired power and district-heating plants is relatively common in Denmark, Finland, Germany, Netherlands and Sweden. RDF is only co-incinerated in boilers producing steam. The substitution varies between 0 and 100%. However, the main drawback of RDF combustion is the corrosion on the surface of heat exchanger in the boiler caused by acidic gas such as HCl. Moreover, the presence of HCl may also stimulate the formation of dioxin.

RDF quality used in power plant depends on type of power plants. For example, hard coal-fired power plant needs higher quality of RDF than fluidized bed incinerator or lignite fired power plants. In the coal-fired power plant, coal is first milled to a fine powder, which increases the surface area and allows it to burn more quickly. In these pulverised coal combustion systems, the powdered coal is blown into the combustion chamber of a boiler where it is burnt at high temperature. The hot gases and heat energy produced converts water in tubes lining the boiler into steam.

The high-pressure steam is passed into a turbine containing thousands of propeller-like blades. The steam pushes these blades causing the turbine shaft to rotate at high speed. A generator is mounted at one end of the turbine shaft and consists of carefully wound wire coils. Electricity is generated when these are rapidly rotated in a strong magnetic field. After passing through the turbine, the steam is condensed and returned to the boiler to be heated once again.

2.11. Summary of Literature Review

The literature confirmed that hazardous wastes may have calorific value more than 8.000 kJ/kg. Even though the potential to recover energy from hazardous wastes are high, the level of recovery is still low due to the regulatory requirements as these wastes may contain significant levels of heavy metals and other impurities which are detrimental to the environment. If these impurities are managed appropriately, the hazardous wastes can be a good source of energy especially for large volume consumptions in power and cement plants. This can be carried out by producing refuse derived fuel (RDF), which can be a potential replacement for coal. Any attempt to recover the energy requires in depth study including RDF production process and subsequent formulation and characterization study. Furthermore, Information on hazardous waste derived RDF from environmental and economic perspectives are not currently available conclusively. All these dimensions form the justification this work. In conclusion, this study aims to confirm if alternative fuels developed from hazardous waste can replace conventional fossil fuels or co-firing with coal in the cement kiln and power stations, reducing CO_2 emissions.

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this chapter, the material and methods used for the experiments and analyses have been presented. The raw materials and selection procedure used for raw materials manufacture were listed in the first part of the chapter. The experiments are designed using response surface methodology, and Central Composite Design (RSM-CCD) based on the selection criteria developed. The final section discussed the reliability study on RDF usage in a cement manufacturing plant.

3.2 Study Framework

To achieve the objectives, the study was divided into three main parts namely, selection and characterization of raw material; RDF production; and utilization and efficiencies assessment of co-combustion of mixture of RDF and coal in the cement kiln. The RDF developed in this study compared with the RDF produced from other resources as well. The main steps of the study are shown in Figure 3.1.

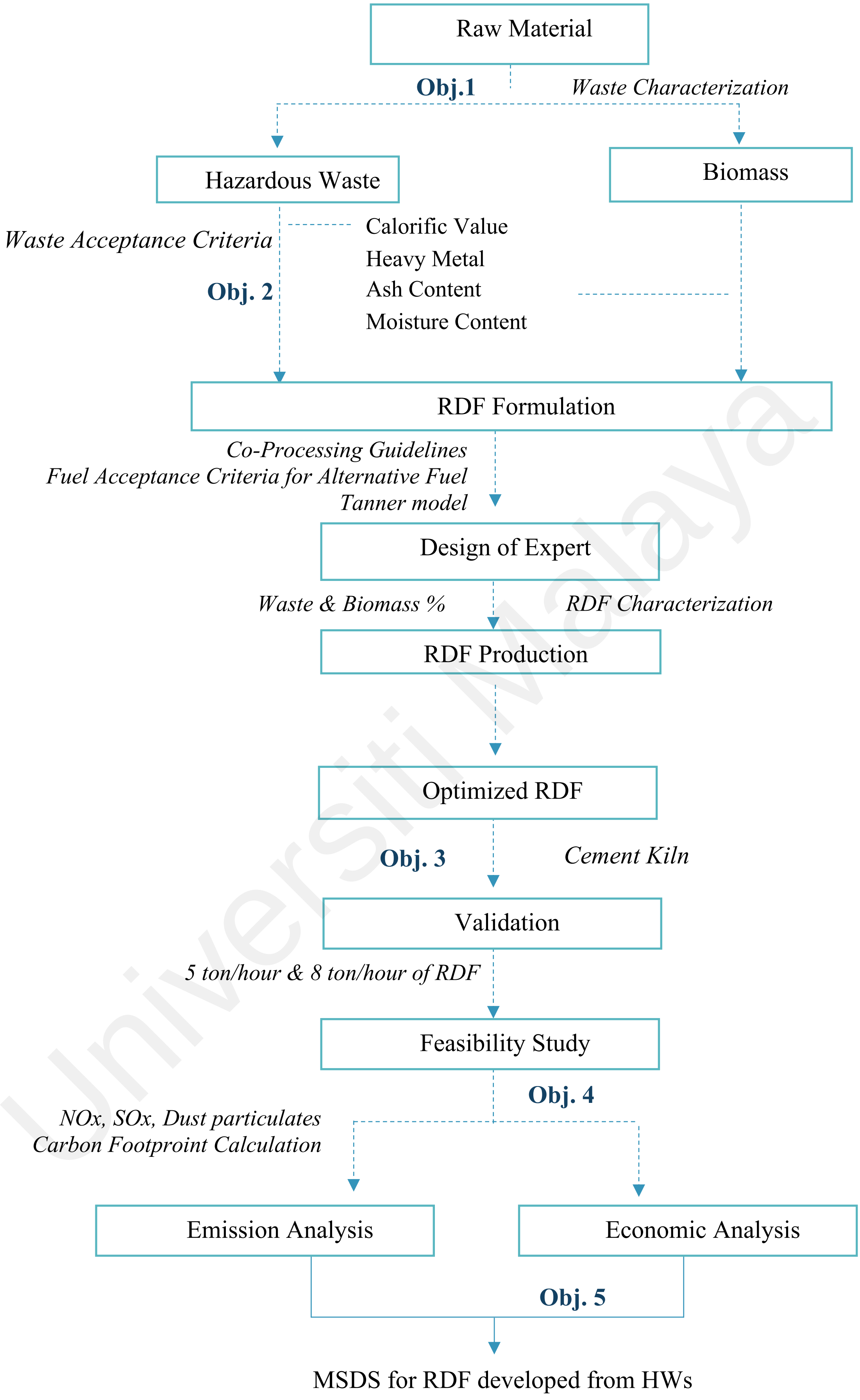


Figure 3.1: Diagram of overall research methodology

3.3 Raw Materials

The most common alternative fuels used in cement kilns are waste oils, plastics, tyres, shredded residues and sewage sludge (El-Salamony, Mahmoud, & Shehata, 2020; Xiong et al., 2017). The feedstock used in this study was a mixture of five types of hazardous industrial waste (rubber waste, mixed waste, paint sludge, palm oil refinery sludge, and wastewater treatment plant sludge) and three types of biomass (sawdust, paddy husk, and empty fruit bunch). The freshly delivered waste has been undergone the screening process. The selection criteria were used to choose the incoming waste. **Table 3.1** shows the types of raw material used in this study to produce RDF.

The waste was collected at various factories located in Malaysia. Hazardous waste with a CV value higher than 3000 kcal/kg is selected to be used as raw materials for RDF production. The waste that does not meet the requirement or the waste acceptance criteria was disposed to HW management center. Two kilograms of each fraction were reserved for the physicochemical and thermophysical analyses. The ASTM E829 standard was used to determine the quantity of samples. The raw materials were packaged and sealed to preserve product qualities, labelled, and sent to the lab for moisture, proximate, heating value, ash and elemental composition analysis

Table 3.1: Description of raw materials

Types of raw materials	**Code**	**Description**	**Sources**
Waste 1: Wastewater treatment plant sludge	SW204	It contains one or several metals, including chromium, copper, nickel, zinc, lead, cadmium, aluminium, tin, vanadium and beryllium	Metal manufacturing, polymer, oleochemical
Waste 2: Rubber waste	SW321	Rubber waste, latex waste or sludge containing organic solvents or heavy metals	Rubber processing
Waste 3: Palm oil sludge	SW204	Uncured epoxy resin and phenolic resin waste of organic phosphorus compound that contains organic solvents or heavy metals	Oleochemical Chemical Industry Palm Oil Industry
Waste 4: Paint sludge	SW416	Waste inks, paints, pigments, lacquer, dye, or varnish	Automotive, paint
Waste 5: Mix wastes	SW421	A mixture of scheduled waste, which includes sludge and resin	Polymer, automotive
Biomass 1: Sawdust	N/A	Waste wooden pallets	Sawmill, furniture manufacturing
Biomass 2: Paddy husk	N/A	The most common lignocellulose materials	Rice mill
Biomass 3: Empty fruit bunch	N/A	Fibrous materials. It contains chemical and mineral additives	Palm oil mill

3.4 Design of Experiment and RDF Formulation

Response Surface Methodology (RSM) is a mathematical and statistical analysis to design the experiment. RSM provides a practical experimental design with a limited number of experiments to provide sufficient response measurements and develop a mathematical model for empirical data (Zhou, Zhang, Li, & Zhao, 2020). Therefore, it is the most economical and effective technique for exploring various input factors and optimizing the experiments. In this study, Central Composite Design (CCD) in the Design-Expert software was selected to optimize the RDF composition. The experimental outputs are investigated using response regression of a 2nd order polynomial model for accurate prediction.

Table 3.2 shows the independent variables chosen in this study and the minimum and maximum values selected for each variable. The CCD model proposed 542 experiments. Each factor's values are coded to standard values that vary from (-1) that corresponds to the minimum level up to (+1) that suit the maximum level in the selected range of parameters. A total of five hazardous waste from the categories described in table 3.1 and three biomass types were used in this study. Their operating parameters ranges were selected based on the availability of the HWs in Malaysia and the disposal fee charged for the waste. Since one of the primary purposes of this study is to identify the best method to dispose of the hazardous waste without being dumped illegally, due to its higher CV value, the lowest moisture content and abundance in Malaysia, the paint sludge is selected as the most elevated, among the other hazardous waste. On the other hand, the composition was also determined based on economic viability, as the disposal fee for paint sludge is higher than others. The biomass was also selected based on lowest cost, as it will be bought at the higher price relative to the HWs, where the disposal fee for HWs is charged.

ANOVA (analysis of variance) was used to verify the significance of the model. The ANOVA analysis was used to identify each input parameter's significance in single, square and combination forms. The model is selected based on the high value of R-squared, adjusted R-squared and predicted R-squared. A 95% confidence level is taken as the benchmark for the test of significance for predicting various responses. Besides, the optimization study was conducted using RSM's Desirability method by Derringer. The optimum condition was selected based on the highest desirability. The resulting combination of variables for the optimal solution is the most significant variable for the RDF formulation.

Table 3.2: Selected hazardous waste and biomass and their actual and coded levels.

Symbol	**Waste/ Biomass**	**Composition (wt. %) Actual and coded levels**		
		-1	**0**	**+0**
A	Palm oil Sludge	0	10	20
B	Rubber Waste (Synthetic Rubber)	0	10	20
C	Wastewater Treatment Plant Sludge A	0	10	20
D	Paint Sludge	0	40	80
E	Rubber Waste (Natural)	0	10	20
F	Wastewater Treatment Plant Sludge B	0	10	20
G	Mixed Waste	0	10	20
H	Biomass (Rice Husk)	0	5	10
I	Biomass (Palm Fibre)	0	5	10
J	Biomass (Saw Dust)	0	5	10

3.5 RDF Production Process

RDF production processes consist of seven steps including manual separation, size reduction, drying, additive mixing, and thermal bio fusion. Figure 3.2 shows the simplified process diagram to produce RDF. The process starts with raw materials receiving hazardous waste with an estimated 30% solid and about 70% moisture, and 70% solid and 30% moisture from biomass. The waste is weighed based on the type and then tested for calorific value and segregated.

The raw materials are stored in loose form to reduce the moisture content by about 5%. After the raw material, characteristics are known. Before production, these raw materials are formulated in raw material mix and quantities for a pilot run. The sources of raw materials and other information are recorded. Upon completing the pilot run, the primary products are tested against the product specifications to ensure product quality. If the product quality is met, the mass production run commences. Whereas if product quality is not met, reformulation takes place, and the process is repeated. This process is also used to determine suitable raw material from a specific generation source. With information from this process, suitable hazardous waste generators are more effectively identified. Before the milling process is commenced, the hazardous waste (HWs) is unpacked, and the moisture content is analyzed and recorded.

The selected waste is crushed in a milling machine to a size less than 20 mm at a 2.0 to 2.5 Mt/hour rate. The waste will be re-milled if the desired dimensions are not met. Biomass also resized to less than 20 mm at a rate of 0.75 tons/hour. The sorting was performed until a fraction size of about 20 mm because the smaller fractions might be not feasible as reported by (Hemidat et al., 2019). The waste and biomass were resized to 20 mm to have a larger surface area and mix the waste and biomass uniformly. Additionally, this size helps go through the thermos bio fusion or briquetting unit as it evenly compresses and generates a consistent calorific value. It is crucial to produce a uniform RDF for feeding alternative feeding lines at a cement plant.

Before the shredding process, the manual separation for foreign matter contaminants was conducted. The crushed hazardous waste and the shredded biomass is transferred into a rotary dryer for drying purposes. The drying process has been done separately for each material. The HWs and biomass weight is expected to be lost at a rate of 0.9 Mt/hour and 0.15 Mt/hour after the drying process. The moisture content of each material will be reduced to 15%, respectively. Each dried material containing a moisture content of more than 15% undergoes the second time's drying process. The dried materials at a rate of 1.4 Mt/hour for HWs and 0.6 Mt/hour for biomass were then transferred to a storage area where the weighing process was held for the thermal bio fusion process. The principal task of the rotary dryer is to reduce the moisture content of the raw materials. The inlet air temperature for the process ranges from 250 to 280°C, and the outlet air temperature from the stack ranges from 90 to 120°C. For air pollution control, the dryer has a twin - cyclone and a bag filter to mitigate the dispersal of particulate matters and a wet venturi scrubber system to minimize the odor pollution from the process.

Further, each material weighted according to a specific ratio in the respective hoppers and conveyed to a mixer and mixed until homogenous. The mixed materials were then fed into the thermal bio fusion machine loader. The hopper, installed beside the thermal bio fusion machine above the screw conveyer where the composite material will flow directly into the machine, will run continuously, and produce the product at a rate of 2 to 2.5 tons/hour. In the final packaging process, the finished products are packed into individual packaging of 1 metric ton.

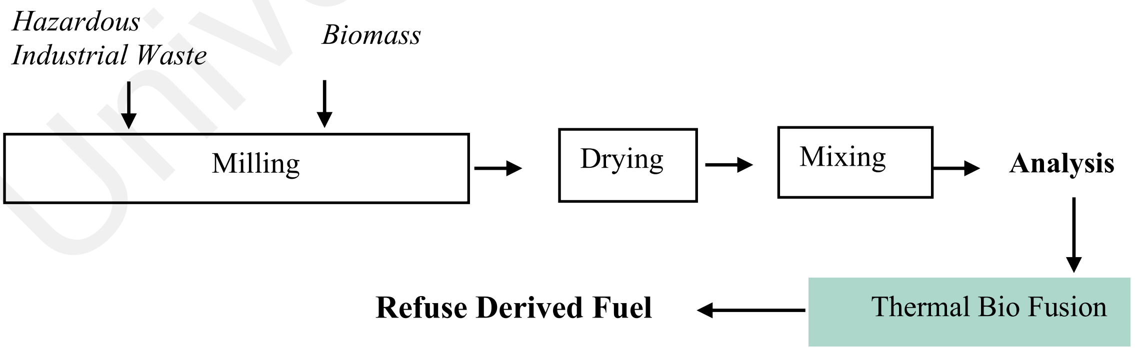


Figure 3.2: Flowchart of the RDF production process

3.6 Application of RDF in the Cement Kiln

3.6.1 Sample Preparation

This study aims to use RDF as an alternative fuel in the cement manufacturing plant and determine RDF performance by assessing RDFs' effect on the clinkering process. In the selected cement manufacturing plant testing was carried out for clinker production using different RDF ratios. Trial validation run was conducted for three months (each validation trial has taken about a day), where RDF is fed into the rotary kiln, together with coal, based on three different conditions as follows:

(a) RDF is fed at a rate of 8 tons/hour.

(b) RDF is fed at a rate of 5 tons/hour.

(c) 100% of coal is fed.

The ratio of RDF and coal mixture as the fuel was calculated based on the percentage of heat replacement should equate to the combustion of 35 tons of coal/hour. Thus, equation (3.1) and (3.2) was used for the calculation.

$$Heat\ replacement_{RDF} = \frac{Heat_{RDF}}{Heat_{RDF} + Heat_{coal}}\ x\ 100\% \qquad (3.1)$$

Where;

$$Heat_{RDF} = Calorific\ value\ \left(\frac{kcal}{kg}\right) x\ Quantity_{RDF}\ (kg) \qquad (3.2)$$

3.6.2 Combustion Process

The cement process involves heat and mass transfer, combustion of fuel, and reactions of clinker compounds and undesired chemical reactions that include sulphur, chlorine, and alkalis. It is essential to understand the cement processes to optimize the cement kiln operation, improve energy consumption, and lower emissions. The process involved in cement production is given in Figure 3.3. Separate lines fed the raw materials, coal and RDF into the preheater & precalciner-kiln system. The preheater & precalciner -kiln system consists of a multi-stage cyclone preheater, and the fuel is burned in two separate stages, at the main burner and the secondary burner. The main burner uses coal, and the secondary burner located at the calciner is used to burn the RDF fed from the RDF feeding storage.

The hot air increases the temperature in the rotary kiln from the main burner. Hence, the secondary burner uses up the energy to heat the raw materials to reduce heat loss in the main kiln. RDF is fed into the secondary burner, helping reduce coal usage. Then the preheated kiln feed is partially calcined (made powdery) in a combustion chamber. And riser duct and then completely calcined in a rotary kiln and heated to approximately 1450 ^{0}C to form clinker. After that, the clinker discharge from the kiln drops onto the grate cooler to reduce the temperature to 120 ^{0}C. Finally, the clinker discharges into the conveyor, and it is transported to the clinker storage. Lastly, the cement clinker is ground as finished cement.

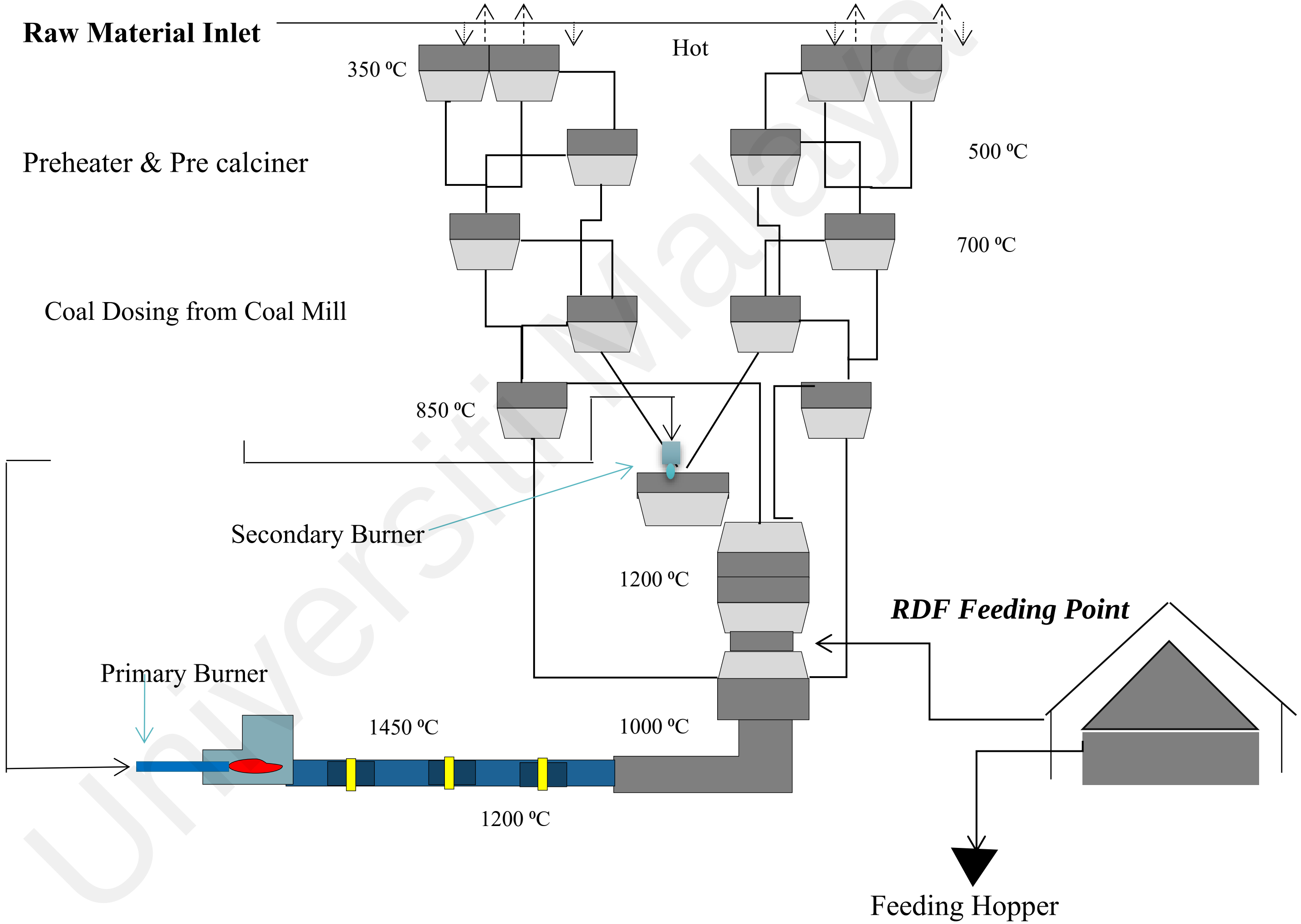


Figure 3.3: Flow diagram of the process in the cement manufacturing industry

3.7 Gas Emission Evaluation in The Cement Kiln

Mathematical modelling was developed to model the combustion of the RDF and coal to predict gases and dust particulates. The modelling parameters are generated from five guidelines: Alternative Fuels Acceptance Criteria (AFAC), TTLC, CAR 1978, CAR 2014, and Co-processing Guidelines. The emission of SO_X, NO_X and dust particulates were analyses through an onsite online stack analyzer. There are several assumptions made in designing the mathematical modelling. First, it was assumed that oxidation reaction happened in the kiln for all heavy metals and other parameters. Thus, the expected stoichiometric stable oxidation reactions are given in equation (3.3) - equation (3.42):

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{3.3}$$

$$C + O_2 \rightarrow CO_2 \tag{3.4}$$

$$H_2O + Cl \rightarrow HCl + OH \tag{3.5}$$

$$S + O_2 \rightarrow SO_2 \tag{3.6}$$

$$4Cr_2 + 3O_2 \rightarrow 2CrO_3 \tag{3.7}$$

$$2Zn + O_2 \rightarrow 2ZnO \tag{3.8}$$

$$2Pb + O_2 \rightarrow 2PbO \tag{3.9}$$

$$Zr + O_2 \rightarrow ZrO_2 \tag{3.10}$$

$$2Sr + O_2 \rightarrow 2SrO \tag{3.11}$$

$$Se_8 + 8O_2 \rightarrow 8SeO_2 \tag{3.12}$$

$$2F_2 + 2H_2O \rightarrow O_2 + 4HF \tag{3.13}$$

$$N + O_2 \rightarrow NO_2 \tag{3.14}$$

$$2N + O_2 \rightarrow 2NO \tag{3.15}$$

$$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3 \tag{3.16}$$

$$4Cu + O_2 \rightarrow 2Cu_2O \tag{3.17}$$

$$2Cd + O_2 \rightarrow 2CdO \quad (3.18)$$

$$2Ni + O_2 \rightarrow 2NiO \quad (3.19)$$

$$4V + 5O_2 \rightarrow 2V_2O_5 \quad (3.20)$$

$$3Sr + N_2 \rightarrow Sr_3N_2 \quad (3.21)$$

$$2Mo + O_2 \rightarrow 2MoO_3 \quad (3.22)$$

$$2I_2 + 3O_3 \rightarrow I_4O_9 \quad (3.23)$$

$$2N + \frac{1}{2}O_2 \rightarrow N_2O \quad (3.24)$$

$$2H_2 + O_2 \rightarrow H_2O \quad (3.25)$$

$$4As + 5O_2 \rightarrow As_4O_{10} \quad (3.26)$$

$$4As + 3O_2 \rightarrow As_4O_6 \quad (3.27)$$

$$2Ba + O_2 \rightarrow 2BaO \quad (3.28)$$

$$Ba + O_2 \rightarrow BaO_2 \quad (3.29)$$

$$3Ba + N_2 \rightarrow Ba_3N_2 \quad (3.30)$$

$$2Sr + O_2 \rightarrow 2SrO \quad (3.31)$$

$$2Sn + O_2 \rightarrow 2SnO \quad (3.32)$$

$$4Sb + 3O_2 \rightarrow 2Sb_2O_3 \quad (3.33)$$

$$Br_2 + 2O_3 \rightarrow O_2 + 2BrO_2 \quad (3.34)$$

$$2Co + O_2 \rightarrow 2CoO \quad (3.35)$$

$$2Te + 2O_2 \rightarrow 2TeO_2 \quad (3.36)$$

$$2Cr_2 + 3O_2 \rightarrow 2Cr_2O_3 \quad (3.37)$$

$$Be(OH)_2\,(s) \rightarrow BeO + H_2O \quad (3.38)$$

$$2Ag_2O(s) \rightarrow 4Ag + 2O_2 \quad (3.39)$$

$$4Tl + O_2 \rightarrow 2Tl_2O \quad (3.40)$$

$$2Hg + O_2 \rightarrow 2HgO \quad (3.41)$$

$$3Mn + 2O_2 \rightarrow Mn_3O_2 \quad (3.42)$$

Secondly, all reactions assumed to be completed combustion due to oxygen being the excess reactant. The case declares operational parameters for the airflow rate studied plant at

750,000 m^3/hour. With 21% oxygen, the volumetric oxygen flow rate is set at 160,050 m^3/hour. Also, it was given by the plant that the mass flow rate of 100% coal is set at 30 tons/hour, at which, when RDF is used, 8 tons/hour RDF will displace 5 tons/hour of coal. To model the quantity of gasses produced from the combustion of fuel in cement kiln, the values from coal results were used, and the modelling was carried out as per the equation (3.43):

The mass flow rate of CHNOS Parameters:

$$\dot{m}_H = H_{\%} \times \dot{m}_F \tag{3.43}$$

Where, $\dot{m}_H$= mass flowrate of CHNO, $H_{\%}$= percentage of CHNOS, $\dot{m}_F$= mass flowrate of fuel.

While assuming for complete combustion, and based on the stoichiometric equation 3.43, the amount of oxygen required for complete combustion can be modelled as equation (3.44) – equation (3.47):

$$\dot{mol}_H = \dot{m}_H \times U_H \tag{3.44}$$

$$\dot{mol}_{O_2} = \dot{mol}_H \times mol_{O_2} \tag{3.45}$$

$$\dot{m}_{O_2} = \dot{mol}_{O_2} \times U_{O_2} \tag{3.46}$$

$$\dot{v}_{O_2} = \frac{\dot{m}_{O_2}}{\rho_{O_2}} \tag{3.47}$$

Where $\dot{mol}_H$ = mole flowrate of CHNO, U_H = atomic mass of hydrocarbon, $\dot{mol}_{O_2}$ = mole flowrate of required oxygen, mol_{O_2} = mole of oxygen for complete reaction, $\dot{m}_{O_2}$= mass flowrate of required oxygen, U_{O_2} = atomic mass of oxygen, $\dot{v}_{O_2}$ = volumetric flowrate of required oxygen, ρ_{O_2} = oxygen density

With the volumetric flow rate established for oxygen, the mass flow rate for the gasses phase in the exhaust gas was calculated with the methods as equation (3.48) – equation (3.52):

$$\dot{mol}_P = \dot{mol}_H \times \frac{mol_P}{mol_H} \tag{3.48}$$

$$\dot{mol}_P = \dot{mol}_P \times U_P \tag{3.49}$$

$$\dot{V}_{air} = v_{air} + A \tag{3.50}$$

$$A = \frac{\pi d^2}{4} \tag{3.51}$$

$$M_{gas} = \frac{\dot{m}_p}{\dot{V}_{air}} \tag{3.52}$$

Where, A = cross-sectional area of chimney, $\dot{V}_{air}$ = volumetric of flue air, v_{air} = velocity of flue air, M_{gas} = concentration of gas produced

Finally, the concentration of gases produced at normal conditions (M_{P_N}) are calculated as equation (3.53):

$$M_{P_N} = \frac{P_O M_P T_N}{P_N T_O} \tag{3.53}$$

Where, P_O = operating pressure, T_N = normal temperature, T_O= operating temperature, P_N = normal pressure.

3.8 Analysis of Raw Materials and RDF

The raw material was characterized according to critical parameters, which are calorific value and moisture content, where the minimum calorific value required is 3000 kcal/kg, while the maximum moisture content is 70%. Further, Total Threshold Limit Concentration (TTLC) of heavy metals in the raw material was also analyzed, where the raw material needs to meet the limits of TTLC as stated in the Guidelines for Application of Special Management of Scheduled Wastes, under Regulation 7(1) of the Environmental Quality (Scheduled Wastes) Regulations 2005. Subsequently, laboratory analysis was conducted according to the Test Method Standard as listed in Table 3.3.

Subsequently, to estimate the heating value, the amount of carbon, hydrogen, oxygen, nitrogen and Sulphur can also be determined using elemental content. Dulong formula used for calculating the heating value (Equation 3.54):

$$Heating\ value_{sample} = 337C + 1419\ (H_2 - 0.125O_2\ ) +\ 93S + 23N \qquad (3.54)$$

Where C, H, O, S and N are % by weight.

RDF produced was characterized by laboratory analysis according to nine groups of parameters and Test Method Standard, as listed in Table 3.4. Further, in order to be used as an alternative fuel in cement manufacturing plants, RDF produced need to meet the specification of the parameters listed in three guidelines which are Guideline for Application of Special Management of Scheduled Wastes under Regulation 7(1) of the Environmental Quality (Scheduled Wastes) Regulations 2005, Guidelines for Environmentally Sound Co-Processing of Scheduled Wastes in Cement Factory in Malaysia, and Fuel Acceptance Criteria for Alternative Fuel from case studied plant.

Table 3.3: Laboratory analysis method

No.	Test Parameter	Method Standard
1.	Calorific Value (kcal/kg)	ASTM E 711-87 (96)
2.	Moisture Content (%)	ASTM E 949-88 (96)
3.	Ash Content (%)	ASTM E 830-87 (96)
4.	Volatile Matter (%)	ASTM E 897-88 (93)
5.	Ash Content (%)	ASTM E 830-87 (96)
6.	Carbon	ASTM 777-87 (96)
7.	Hydrogen	
8.	Nitrogen	
9.	Sulfur	
10.	Chlorine	
11.	Oxygen	ASTM D 3176-89 (97)
12.	Pentachlorophenol	EPA SW 8260B
13.	2,4-Dichlorophenoxy acetic acid	
14.	2,4,5-Trichlorophenoxypropionic acid	
15.	Tetrachloroethylene	
16.	Aldrin	EPA 8081A
17.	Chlordane	
18.	DDT	
19.	DDE	
20.	DDD	
21.	Dieldrin	
22.	Endrin	
23.	Heptachlor	EPA 8081A
24.	Kepone	
25.	Lindane	
26.	Methoxychlor	
27.	Mirex	
28.	PCBs	
29.	Toxaphene	

Table 3.3 (continued)

No.	Test Parameter	Method Standard
1.	Asbestos	EPA SW 8260B
2.	Fluoride salts	
3.	Organic lead	

3.8.1 Calorific Value Determination

The calorific value was tested using a bomb calorimeter (IKA, Germany). The bomb calorimeter will provide Higher Heating Value (HHV). The Lower Heating Value (LHV) was determined by using the HHV, hydrogen content and moisture obtained from the bomb calorimeter. The analysis was duplicated. LHV of the samples were determined by using Eq. 3.55 and 3.56.

$$LHV_{Dry} = HHV_{Dry} - 2441.8\ X\ \frac{9H_{Dry}}{100} \tag{3.55}$$

$$LHV_{Wet} = LHV_{Dry}\ X\ \frac{100-W}{100} - 24.42W \tag{3.56}$$

Where: HHV_{dry} is the HHV of a dry sample (kJ kg^{-1}), LHV_{dry} is the LHV of a dry sample (kJ kg^{-1}), H_{dry} is the weight percentage of hydrogen, LHV_{wet} is the LHV of a wet sample, and W is the percentage of moisture in the sample. Heat energy for the vaporization of water is 2442 kJ kg^{-1}.

3.8.2 Chlorine Determination

The chlorine content in the raw material and waste were analyzed using a combination of High-Pressure Decomposition Device (HPDD) Method with ion chromatography (IC) based on ASTM Standard (ASTM 777-87 (96)). A bomb Calorimeter was used to perform HPDD Method. 5 mL of 50g/L sodium carbonate solution was added to the 0.8 g of sample to absorb chlorine gas produced during combustion. The solution in the bomb was collected in a beaker by rinsing the interior of the bomb, the sample cup and the lid with deionized water. The collected solution from Bomb Calorimeter was collected in a beaker and filtrated through a 0.45 µm filter paper. After that, the 50 mL with deionized water was added and tested for chloride content using an IC analyzer.

3.8.3 Ash Content

The composition, destination and potential risks of the residual ash are assessed. Any heavy metals that are present may be concentrated in the ash. The ash content of the samples was determined using Thermo Gravimetric analysis. The total ash analysis was analyzed using ASTM E830-87 (96) standard. The sample was placed in a muffle furnace at a low temperature, and the temperature has gradually arisen to 7000 °C. After igniting for half an hour at a temperature between 7000 °C and 7500 °C, the remaining is cooled down and weighted. Ash content is measured according to the formula as in equation (3.57).

$$Ash\ content_{sample} = \frac{mass_{ash}}{mass_{sample}} \times\ 100\% \qquad (3.57)$$

3.8.4 Moisture Content

The moisture content of waste can reduce the effectiveness of combustion in the initial stages, as energy is taken up by the creation of steam. Thus the calorific value and burning efficiency must account for the moisture content, which detracts from the overall amount of energy that can be extracted. Therefore, it needs to be stated as the net calorific value. Additionally, higher moisture content means the material will burn at a lower temperature and thus increase the possibility of dioxin and furan formation. Moisture analyzers are used to measure the moisture content of the waste sample, where the analyzer incorporates an electronic balance with a sample tray and surrounding heating element. Under microprocessor control, the sample can be heated rapidly, and a result computed prior to the completion of the process, based on the moisture loss rate.

3.8.5 Heavy metals content

Table 3.4 summarized the standard analysis method used for heavy metal analysis. Prior to analysis, samples must be solubilized or digested using appropriate sample preparation methods. Duplicates were carried out for each sample.

3.8.6 Elemental Analysis

The carbon, hydrogen, and nitrogen contents of raw materials were determined using a Euro EA 3000 series, Elemental Analyzer (German), based on ASTM 777-87 (96).

3.9 Clicker Quality Analysis

Online analysers that apply X-ray fluorescence (XRF) and/ or X-ray diffraction (XRD) techniques is used to ensure quality control in the cement manufacturing process. Online quality control of cement requires that the mineral contents of cement clinker such as C3S, C2S and free lime be measured real time.

3.9.1 X-Ray Fluorescence

The chemical elemental analysis of cement clinker is analysed using the X-ray fluorescence technique (XRF). Concentrations of the main oxides can be determined using XRF analysis. Because mineralogical information cannot be detected by XRF, the Bogue equation is utilised to determine the potential compositions of clinker phase minerals.

Table 3.4: Heavy metal analysis method

Heavy metals (mg/L)	**Analysis method**
Chlorine, Cl	ASTM 776-87 (96)
Arsenic, As	EPA 6010B
Barium, Ba	
Berylium, Be	
Bromides, Br	
Cadmium, Cd	
Chromium-IV, Cr	
Chromium-IV, Cr^{6+}	
Cobalt, Co	
Copper, Cu	
Fluorine, F	
Iodin, I	
Lead, Pb	
Manganese, Mn	
Mercury, Hg	
Molybdenum, Mo	
Nickel, Ni	
Selenium, Se	
Silver, Ag	
Strontium, Sr	
Tellurium, Te	
Thallium, Th	
Tin, Sn	
Vanadium, V	
Zinc, Zn	
Zirconium	

3.9.2 X -Ray Diffraction

X-ray diffraction (XRD) is a common technique for measuring mineral content. The technique involves firing an X-ray beam is fired onto a sample and then the diffraction pattern is measured. A sample is collected, prepared and analyzed. The composition of the sample is determined from the diffraction pattern. This technique is highly developed and able to detect most cement minerals, even distinguish between the different phases of aluminates, belite and gypsum.

3.10 The Life Cycle Assessment

The Life Cycle Assessment (LCA) methodology was used to calculate the Carbon footprint of RDF production. Carbon Footprint standard ISO 14067 (The Carbon Footprint of a Product) provides a standardized method for quantifying the total greenhouse gases (GHG) emissions generated during the life cycle assessment of a product (Šerkinić, Majić Renjo, & Ucović, 2020). The life cycle stage includes cradle to grave, cradle to gate, gate to gate, and partial life cycle. The assessment considers all raw materials, transports, manufacturing processes, usage, and disposal of the product. The method excludes the quantification of GHG emissions from the transportation of workers to the workplace, human energy inputs to the process, and wastes generated from the administrative activities in the manufacturing plant (Wang, Wang, & Yang, 2018). The GHG considered in the assessment is listed in IPCC, defined as a global warming potential of 100 years. The gases are expressed as CO_2 equivalent (CO_2-eq).

The GHGs emission was assessed based on the Intergovernmental Panel on Climate Change (IPCC) method. An excel based model calculator was developed as a tool to calculate GHG emissions from the RDF life cycle. The result obtained in this study is based on 1000 ton of RDF. Figure 3.4 summarizes the stages involved in the excel model calculator. The global warming potential of carbon dioxide equivalent emissions in this study uses the IPCC Fifth Assessment Report values as summarized in Supplementary Table 3.5 (IPCC, 2014).

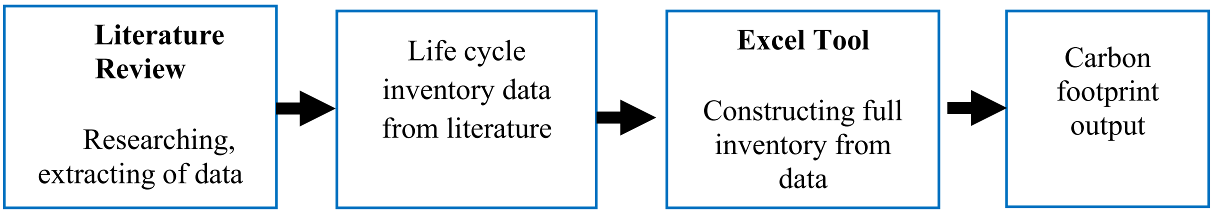


Figure 3.4: Excel model calculator

Table 3.5: Global warming potential (GWP) values relative to CO_2

Greenhouse gases	GWP values for a 100-year time horizon
Carbon dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous oxide (N_2O)	265

3.10.1 Functional Units

The functional unit for this study provides a quantified reference for all relevant inputs and outputs for the complete life cycle of RDF. The available unit is defined as a kilogram of carbon dioxide equivalent per megajoule of energy generated from the complete combustion of RDF. CF is expressed in kg CO_2 eq/MJ.

3.10.2 System Boundary and Time Frame

The system boundary for evaluating the carbon footprint of RDF starts with the waste collection from the selected industry, manufacturing of RDF, and utilization of RDF in the cement plant is illustrated in the Figure 3.5. The manufacturing flow of the RDF is explained in the Figure 3.6.

The carbon footprint quantifies greenhouse gas emissions, including CO_2, N_2O and CH_4 emitted from the complete life cycle of RDF, expressed as carbon dioxide equivalent (CO_2-eq). The detailed sources of CO_2-eq emissions according to every stage of the life cycle of the RDF are summarized in Table 3.7. It should be noted that under oxidative burning of RDF, methane is not expected to be released. Data sets used for this study are based on complete data for 12 months.

3.10.3 Raw Materials Supply

Raw materials used to produce RDF are a combination of hazardous wastes, and biomass from industries in Malaysia. The types, code, and source of raw materials used in this study will be discussed in the result and discussion section. The freshly delivered waste has undergone the screening process, and the selection criteria were used to choose the waste. Guidelines for Application of Special Management of Scheduled Wastes under Regulation 7(1) of the Environmental Quality (Scheduled Wastes) Regulations 2005, Guidelines for Environmentally Sound Co-Processing of Scheduled Wastes in Cement Factory in Malaysia Fuel Acceptance Criteria (FAC) for Alternative Fuel from Cement Plant have been used to develop the selection criteria of waste and specification of RDF. The minimum calorific value of the waste was 10.46 MJ/kg, a minimum volatile matter of 30%, and maximum sulphur, ash, and moisture levels of 3%, 25%, and 30%, respectively. And the minimum calorific value of biomass used in this study was 12.55 MJ/kg.

Table 3.6: Sources of CO_2-eq emission according to life cycle stages

Life cycle stages	**Sources of CO_2-eq emission**
Raw materials supply	Vehicle fuel consumed for transportation of raw materials to RDF manufacturer.
Manufacturing	Water, electricity, and fuel consumed for facilities, and energy is consumed for on-site vehicles.
Distribution to consumer	Vehicle fuel is consumed for the transportation of RDF to the cement manufacturing plant.
Utilization	Combustion of RDF for the cement rotary kiln operation.
Disposal of wastes generated from manufacturing plant	Vehicle fuel is consumed for transportation of wastes to disposal facility and emissions released from the incineration of wastes.
End of life	Emissions are released from the incineration of ash residues generated from the utilization of RDF. However, the RDF is fully utilized in cement rotary kiln and did not generate any ash residue in this study. Thus, no emissions from this life cycle stage are evaluated in this study.

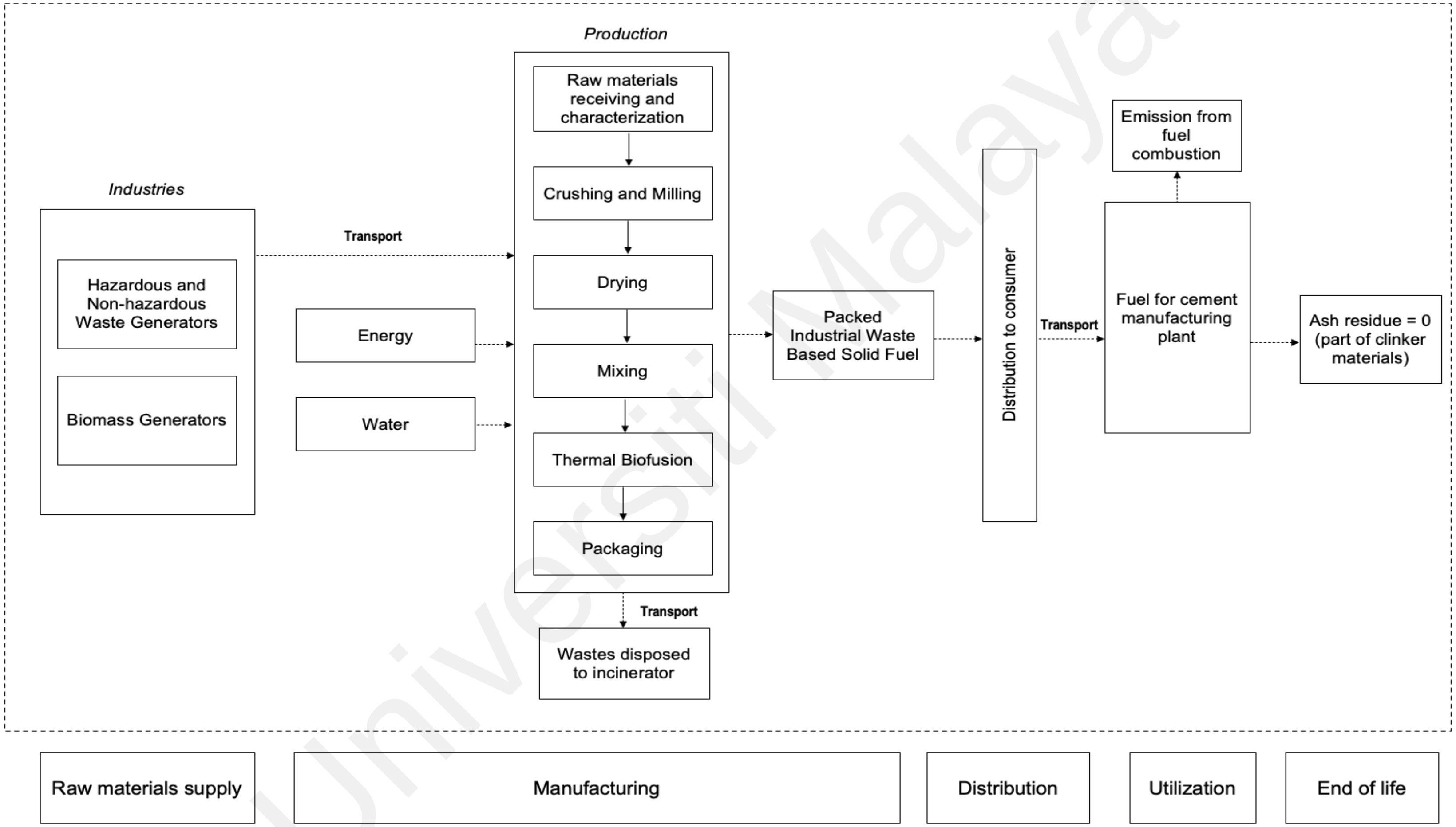


Figure 3.5: A schematic overview of the RDF supply chain and the system boundary

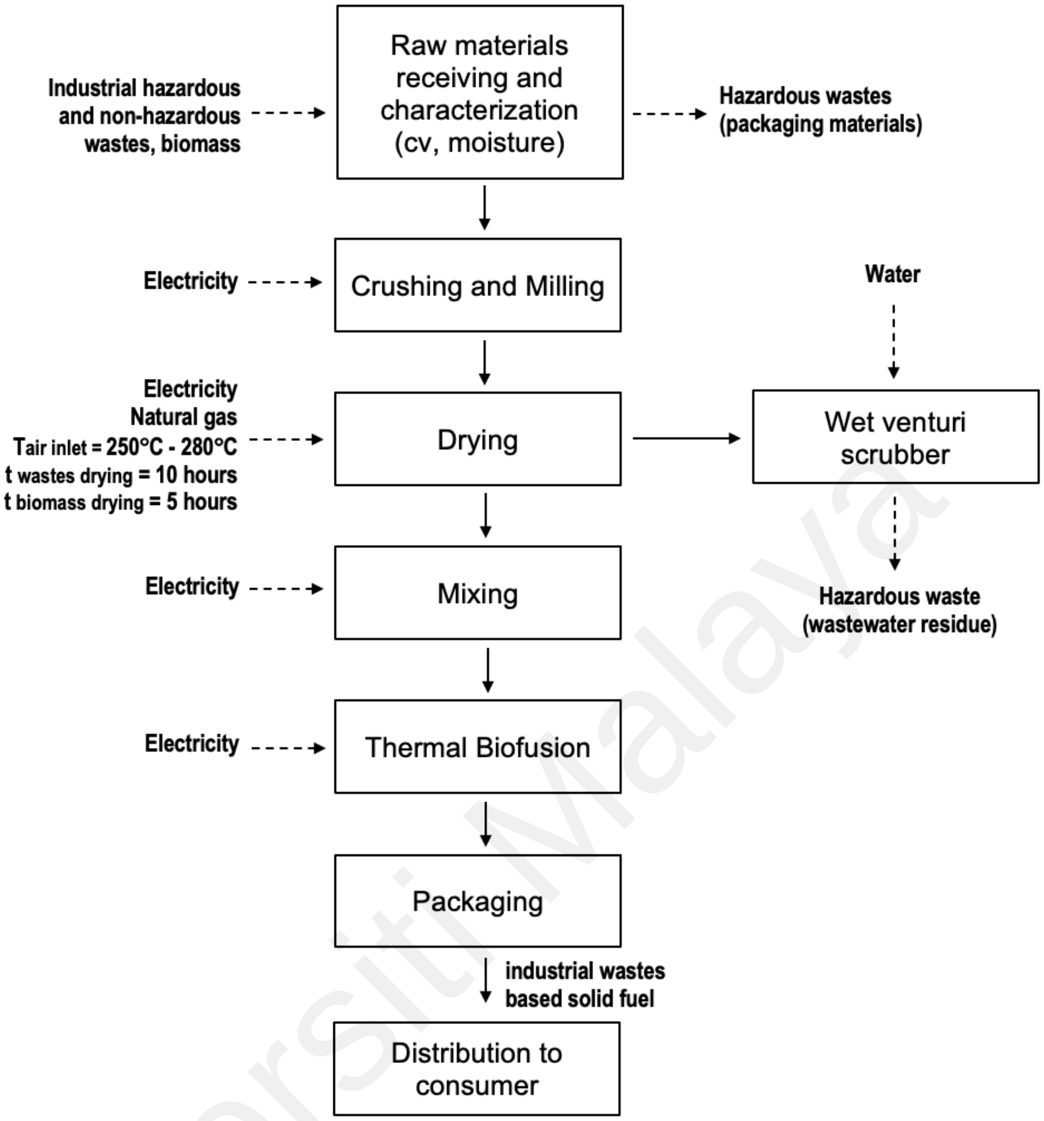


Figure 3.6: Manufacturing process flow of RDF

3.11 Determination of Carbon Footprint

3.11.1 Disposal of Wastes

Wastes generated from the manufacturing activities include packaging material from the incoming industrial wastes and residue from the wet venturi scrubber. Licensed contractors collect the wastes classified as hazardous wastes with the frequency of collection of 47 times a year. In this study, the waste generated is assumed to be incinerated at the disposal facility.

3.11.2 End of Life

The RDF is fully utilized during the cement rotary kiln operation. The ash residues generated during solid fuel combustion are also part of the cement clinker materials. This can be supported by (Lam & McKay, 2010), which has studied the feasibility of replacing clinker raw materials with ash residue for cement clinker manufacturing. Therefore, the end-of-life of RDF does not generate any ash residue from the utilization stage.

3.11.3 Transportation

Transportation is divided into three stages; 1) transportation of raw materials from wastes and biomass generators to the manufacturing plant using a company-owned diesel-fueled lorry, 2) transportation to the consumer, and 3) transportation of hazardous waste generated from the manufacturing plant to the waste disposal facility using the third party owned diesel-fueled lorry. Table 3.7 shows the details of transportation included in this study, according to respective stages.

Table 3.7: Details of transportation

Life cycle stage	Type of vehicle	Capacity (MT)
Raw materials to manufacturing plant	40' and 20' lorry	8.5 and 16
RDF manufacturer to consumer	40' lorry	30
Disposal of wastes generated from manufacturing plant to the disposal facility	5' lorry	1

3.11.4 Summary of Materials and Energy Flow

Table 3.8 shows the input-output of materials and energy flows and other related information involved in this study. Hence, the calculation for quantifying CO_2-eq emission generated is using the data summarized in Table 3.8.

Table 3.8: Input-output details

Life cycle stage	**Sources of CO_2-eq emission**	**Quantity per year**
Raw material supply	Wastes	12,338.1 MT
	Biomass	2,490.3 MT
Transport, TP1 $_{\text{RMG to SFM}}$	Total distance	419,805.8 km
	Fuel consumption	138,329.3 L
Transport, TP2 $_{\text{SFM to SFC}}$	Total distance	82,400.0 km
Transport, TP3 $_{\text{SFM to WDF}}$	Total distance	28,668.0 km
Manufacturing of RDF	Water consumption	1,506.0 m^3
	Diesel consumption	25,231.7 L
	Petrol consumption	2,559.4 L
	Natural gas consumption	7,615.0 mmBtu
	Electricity consumption	392,915.0 kWh
Utilization of RDF	Solid fuel output	12,330.0 MT
Waste disposal	Scheduled waste	257.3 MT
End of life	Ash residue	0

3.12 Safety Precautions

The following Safety Operation Procedure (SOP) was adhered throughout the work:

1. SOP of the cement plant during the validation experiments.
2. MSDS to determine relevant safety measures for handling hazardous waste throughout the work.
3. RDF manufacturing company policies and material handling methodologies.
4. Requirements of other standards.
5. During the Covid 19 period SOP issued by the university was used in conducting the work.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Characterization of Raw Material

The hazardous (HWs) and non-hazardous waste samples were collected from the different premises located in Peninsular Malaysia. The waste is segregated based on organic matter, inorganic matter, and other materials using manual and mechanical procedures. Table 4.1 shows the detail of raw materials used in this study. As shown in the Table, in this study, five types of hazardous waste and three biomasses have been used. The waste was chosen because it is readily available in Malaysia and contains a major element for the processing and recovery of RDF after initial screening. The raw material is chosen based on the special waste management and co-Processing Guidelines.

The calorific value and moisture content of the raw materials were set to be with a minimum calorific value of 3000 kcal/kg and a maximum moisture content of 30%. Total Threshold Limit Concentration (TTLC) of heavy metals in the selected raw material were also analyzed. Industrial waste streams may contain heavy metals such as Pb, Zn, Co, Ni, Sb, Cr, Cu, etc. Many wastewaters contain copper, including those from electronics plating, paint manufacture, and printing processes. Industrial processes and the chemical sector could contribute to the presence of nickel in waste. Because nickel is found in oxide form and is easily leachable, nickel-containing waste is classified as hazardous waste and may cause heavy metal contamination. These heavy metals pose severe health implication when releaser into environments, therefore TTLC is important for handling of waste and RDF.

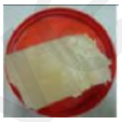
The concentration of heavy metals in hazardous waste must be considered while evaluating the environmental consequences of RDF use before and after usage in the cement kiln. Quantifying heavy metals in hazardous waste is critical because it contributes to the production of clinker’s quality in cement plant. In the production of RDF, heavy metals may also cause fouling, corrosion, and pollutant emissions. Thus, the waste acceptance criteria established by the Malaysian Department of the Environment (DOE, 2015) was used to select and characterize hazardous waste in this study. The values limit for important parameters and heavy metals in hazardous waste are shown in Table 4.2. As shown in Table 4.2, mercury is permitted in concentrations up to 20 parts per million (ppm) in the hazardous waste. This might be because the mercury can be transferred into fly ashes. Number of studies found that characterizing and reclassifying waste is important to improve the quality of bottom ash residue that contains heavy metals (Siddiqui et al., 2012).

Furthermore, the proximate analysis was used to identify volatile matter, fixed carbon, and ash content of the raw materials. The results of proximate analysis and calorific value of the raw materials are listed in Table 4.1. All the waste and biomass used in this study have a minimum CV of 9000 kJ/kg. As can be seen in Table 4.2, the natural rubber waste has the highest calorific value of 33,643 kJ/kg, followed by synthetic Rubber waste (26,154 kJ/kg), mixed waste (18,920kJ/kg), and palm oil sludge (18,200kJ/kg). And natural rubber contained the highest percentage of the volatile matter of 89%, and Palm fiber revealed to have a higher content of fixed carbon (18 %) and ash content (5.5 %) compared to other biomass and waste. This is since rubber contains more than 90% organic content and can produce excellent calorific fuel(Eddie, 2014).

Table 4.1: Waste Acceptance Criteria

Parameters	**Symbol**	**Unit**	**Values**
Calorific Value	CV	kcal/kg	2000 (min)
Sulphur	S	%	2 (max)
Volatile matter	VM	%	30 (min)
Antimony	Sb	ppm	2,000
Chromium	Cr		5,000
Lead	Pb		1,000
Arsenic	As		5,000
Copper	Cu		30, 000
Selenium	Se		100
Nickel	Ni		30, 000
Chlorine	CI		10, 000
Fluorine	F		
Bromides	Br		
Iodin	I		
Zinc	Zn		5000
Mercury	Hg		20
Cadmium	Cd		100
Barium	Ba		10, 000
Lead	Pb		6,000
Chromium-VI	Cr		500
Argentum	Ag		500
Vanadium	V		24, 000

Table 4.2: Characteristics of waste and biomass used for the production of RDF

ID	Waste		CV (kJ/kg)	VM (%)	FC (%)	Ash (%)
Hazardous waste						
A		Palm Oil Sludge	18,200	75.0	18	15.22
B		Rubber Waste Synthetic	26,154	85.0	15	10.00
C		Waste water treatment Sludge A	9,121	50.2	5	32.00
D		Paint Sludge	18,800	73.0	10	28.80
E		Rubber Waste Natural	33,643	89.0	10	5.00
F		Waste Water Treatment Sludge B	17,392	77.0	14	34.00
G		Mixed waste	18,920	80.0	12	12.00
Biomass						
H		Rice husk	13,388	68.0	16	16.10
I		Palm Fibre	18,828	77.0	18	5.50
J		Saw Dust	16,736	70.30	16	10.35

Hazardous substances, such as heavy metals, are found in rubber product production wastewater, which are generated from chemicals in latex preservation and compounding processes. In comparison to magnesium, iron, copper, nickel, and manganese, which were detected in smaller concentrations, zinc was detected as the primary heavy metal component in the rubber waste, which is consistent with the findings of this study.

The heavy metal analysis of hazardous waste and biomass used in this study is shows in Table 4.3. As revealed by the analysis, the natural rubber was contained highest amount of copper which is 121.54 ppm followed by synthesis rubber waste (64 ppm), waste water treatment sludge A, paint sludge and waste water treatment sludge B. On the other hand, the concentration of chromium is highest in the wastewater treatment sludge A (352.1 ppm), followed by synthetic rubber waste (146 ppm). pH, biomass concentration, presence of organic compounds or other heavy metals, contact time have all been discovered as influencing chromium toxicity in activated sludge (Vaiopoulou & Gikas, 2012) . Besides, the concentration of nickel (1165 ppm) and argentum (51.8 ppm) also highest in the wastewater treatment sludge A compared to other hazardous waste.

Table 4.3: Heavy metal content of hazardous waste

Type of Waste	SW Code/Description	CV (Kcal/kg)	As	Ba	Cd	Cr	Cu	Pb	Hg	Ni	Se	Ag	Zn
TTLC			500	10,000	100	2500	2500	1000	20	2000	100	500	5000
A	SW 204	4,350	0.018	2.80	0.01	3.24	2.690	0.01	0.018	12.20	0.01	0.01	60.5
B	SW 321	6,250	0.018	0.01	0.01	336.70	0.340	0.01	0.018	0.01	0.01	0.01	104.4
C	SW 204	2,180	0.250	3.60	0.01	1,302.00	32.500	0.01	0.018	16.70	0.01	0.01	393.4
D	SW 416	4,493	0.018	0.01	0.01	3.34	14.400	2.50	0.018	0.02	0.01	0.01	24.1
E	SW 321	8,041	0.018	2.50	0.01	1.00	4.100	0.01	0.018	0.02	0.01	0.01	6.1
F	SW 204	4,157	0.018	12.90	0.01	1.93	13.300	0.01	0.018	1.43	0.01	0.01	118.4
G	SW 421	4,521	0.018	0.01	0.01	0.01	1.950	0.01	0.018	0.01	0.01	0.01	1.2

4.2 Refuse Derived Fuel Specification

RDF specifications were developed with parameters that were listed in the guidelines based on the waste acceptance criteria. Three guidelines as summarized in Table 4.4 have been used to develop the RDF specification in this study. The amount of HWs is below the maximum permissible concentration of (HWs) to be recovered/recycled or disposed at a licensed premise, according to the ‘Guidelines for Application of Special Management of Scheduled Wastes under Regulation 7(1) of the Environmental Quality (Scheduled Wastes) Regulations 2005'. The waste generators should apply to the Director General to have the scheduled wastes generated from their facility excluded from being treated, disposed of, or recovered in premises or facilities other than at the prescribed premises or on-site treatment or recovery facilities. Therefore, it is important to enclose the amount of HWs generated in the premise to get the approval from DOE.

The RDF specification developed in this study is illustrated in the Table 4.5. The RDF specifications developed in this study were compared against RDF Guidelines in Europe. The results of the comparison are tabulated in the following Table 4.6. Currently, there are no guidelines for RDF standard in Asia, thus the European guidelines were used. Besides, a comparison against coal specifications based on Australian coal product typical analysis also had been carried out. Based on the comparison study conducted it is revealed that that the quality of RDF developed form hazardous waste is very much at the same level, if not higher than the coal compared above. The high calorific values and remarkably low ash content will be able to provide the industries with an alternative fuel to coal.

Table 4.4: Guidelines used for the development of RDF specification

No.	**Guidelines**	**Justification**	**Reference**
1	Guidelines for Application of Special Management of Scheduled Wastes under Regulation 7(1) of the Environmental Quality (Scheduled Wastes) Regulations 2005.	Maximum allowable concentration of scheduled wastes (HWs) to be recovered/recycled or disposed at a licensed premise.	(DOE, 2015)
2	Guidelines for Environmentally Sound Co-Processing of Scheduled Wastes in Cement Factory in Malaysia	RDF can be processed in an environmentally sound manner as alternative fuel to coal in the cement kilns.	
3	Fuel Acceptance Criteria (FAC) for Alternative Fuel from Cement Plant.	RDF meets the allowable limit of alternative fuel to be used in kiln.	
4.	Tanner model	Tanner triangle for assessment of RDFs, based on the three main quality standards (moisture content (M), ash content (A) and combustible (C))	(Institution, 2011)

Table 4.5: RDF specifications

Types	Analysis	Units	RDF Specification
FAC	Calorific Value	kcal/kg	2500 (min)
	Volatile Matter	%	30
	Sulphur	%	3 (max)
	Ash Content	%	25 (max)
	Moisture Content	%	30 (max)
Heavy metals	Antimony	ppm	150
	Cuprum	ppm	750
	Lead	ppm	300
	Chromium	ppm	750
	Arsenic	ppm	150
	Stanum	ppm	1000
	Selenium	ppm	30
	Nickel	ppm	600
	Cobalt	ppm	2400
	Chlorine	ppm	1000
	Fluorine	ppm	
	Bromides	ppm	
	Iodin	ppm	
	Zinc	ppm	2500
	Mercury	ppm	8
	Cadmium	ppm	30
	Thallium	ppm	250
	Barium	ppm	3000
	Molybdenum	ppm	1000
	Berylium	ppm	25
	Chromium-VI	ppm	150
	Argentum	ppm	150
	Vanadium	ppm	1000

Table 4.6: Comparison of RDF Guidelines Europe and RDF specification developed in this study

Parameters	**Calorific value (MJ/kg)**	**Moisture content (%)**	**Ash content (%)**
RDF	10.5- 31.4	30	25
Finland	13 – 16	25 – 35	5 – 10
Italy	15	max 25	20
United Kingdom	18.7	7-28	12
Australian coal			
• *Mt. Arthur*	24.1 – 25.8	10	12.0 – 17.5
• *Illawara*	24.7 – 28.0	6	21.0 – 23.0
• *Queensland*	25.9 – 27.2	8-11	9.3 – 16.9
Australia Semi soft Coking	30.56	28.9	26.8
Australia Thermal	8-10	8-10	15-18
Indonesia Thermal	8-10	12-15	4.5

4.3 Fuel Acceptance Criteria for Cement Industries

The fuel acceptance criteria for cement industries, as a basis, are in accordance with Table 4.6. Minimum Waste Acceptance Criteria for Scheduled Waste Used as Alternative Fuel and were supplemented with additional parameters by the case studied cement plant. From the Mathematical Modeling, it was concluded that the effect of the parameters with concentration set at the guideline limits, were negligible. Thus, the maximum or minimum values are set to be lower than the values from the guidelines. Thus, RDF specifications are listed in Table 4.6.This is to ensure that the product performs in an environmentally safe and compliant manner as an alternative fuel to coal in case studied cement plant.

4.3.1 Comparison Of Existing Alternative Fuels Used In The Selected Cement Plant With RDF

The selected cement plant using Empty Fruit Bunch (EFB), Palm Fiber, Palm Kernel shell and used tires (both passenger cars and truck and buses) as an alternative fuel material. The moisture contents and net calorific values of some of these alternative fuels are compared against RDF (Table 4.8) as a guide for determining the Acceptance Criteria for RDF (refer to Table 4.1). Table 4.9 summarized the alternative fuel acceptance criteria of a selected Cement Plant used in this study.

Table 4.7: Comparison of Existing Alternative Fuel with RDF

Parameters	**EFB**	**Palm fiber**	**Palm Kernel Shell**	**RDF**
Net Calorific Values (kcal/kg)	3924	4455	4626	2500 (min)
Moisture Content w/w%	58.6`	40.0	22.6	30 (max)

Table 4.8: Alternative Fuel Acceptance Criteria of a selected Cement Plant

Parameter		**Unit**	**Alternative Fuel Acceptance Criteria**
Moisture (as received)		%	70.0 Max.
Calorific Value, CV		kcal/kg	2,500.0 Min.
Volatile Matter, VM		%	30.0 Min.
Ash Content		%	25.0 Max.
Sulfur		%	3.0 Max.
Heavy Metals Content			
Pb	Lead	ppm	5,900 Max.
Cr	Chromium	ppm	1,000 Max.
As	Arsenic	ppm	3,500 Max.
Sn	Stanum	ppm	34,000 Max.
Se	Selenium	ppm	180 Max.
Ni	Nickel	ppm	30,000 Max.
V	Vanadium	ppm	24,001 Max.
Sb	Antimony	ppm	1,800 Max.
Cl	Chlorine	ppm	6,000 Max.
Cu	Cuprum	ppm	13,000 Max.
Zn	Zinc	ppm	80,000 Max.
Hg	Mercury	ppm	15 Max.
Cd	Cadmium	ppm	1,800 Max.
Ba	Barium	ppm	74,500 Max.
Mo	Molybdenum	ppm	9,500 Max.

4.4 RDF Standardization

The RDF standards addresses five major issues including raw material acceptance criteria, product formulation to meet product specification, productions processes, product specifications, and application of product and environmental measurements. It is important to focus on both the inputs to the production of the RDF as well as the output from combustion of RDF. The process of standardization requires proponent to address various aspects regarding inputs to production of RDF such as calorific values and raw material, especially the hazardous waste composition. It is important to confirm that a consistent product is produced from known waste to ensure the combustion process will be effective and efficient, the expected emission is known, and the emission are able to effectively monitored and controlled with appropriate facility design and pollution control equipment. Besides, it's important to have known the input to ensure the products is not highly variable or unpredictable and meets as set if product specification. the waste used also need to be known to ensure the RDF produced has a beneficial net CV, meet the end user fuel acceptance criteria, and does not contravene environments and other regulatory standards throughout the usage.

4.5 Refuse Derived Fuel Formulation

In this study, RSM with a CCD design in the Design-Expert software was used to design the experiment and determine the optimum condition. The independent variables and corresponding responses are listed in Appendix A. The RSM experimental design was fitted to the second-order polynomial model shown in Equation 4.1. A multi regression model of CV, VM, FC, and ash content in percentage is developed using Design-expert, and the result is summarized in Table 4.9.

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{j=1}^{k} \sum_{i=1}^{i<j} \beta_{jj} x_i x_j + \varepsilon$$

(4.1)

Where Y is the response value, Xi is the coded value of the factor, β_0 is the constant, βi linear coefficient, β ii quadratic coefficient, β ij interaction coefficient. The co-efficient parameters can be estimated using multiple linear regression analysis (Buthiyappan & Abdul Raman, 2019).

Table 4.9: Polynomial model equations response variables established

Responses (%)	**Equation**
CV	$40.7 - 4.5A + 4.0B - 4.4C - 2.3D - 1.3E + 2.1F - 2.3G - 1.7H + 3.J$
VM	$40.7 + 4.5A + 4.0B - 4.4C - 2.3D -1.3E +2.1F - 2.3G - 1.7H +3.0I + 7.3J$
FC	$51.5 - 5.7A -5.7 B -1.3C -2.0D + 0.7E + 2.9F + 1.4G + 0.7H+ 0.4J$
Ash	$21.0 - 1.5A +3.3 B -0.3C -0.1D + 1.2F + 0.2G$

Table 4.10: Analysis of variance for the regression model

Response (%)	**F-value**	**Prob. > F**	**Adeq. Prec.**	**R^2**	**Adj. R^2**	**Pred. R^2**	**Model**
CV	386.7	< 0.0001	103.8	0.9747	0.9722	0.9689	Sig.
VM	406.3	< 0.0001	122.1	0.9748	0.9724	0.9693	Sig.
FC	403.1	< 0.0001	121.7	0.9746	0.9722	0.9691	Sig.
Ash	202.1	< 0.0001	80.5	0.9742	0.9713	0.9671	Sig.

The analysis of variance (ANOVA) in Table 4.10 presents that the p-value for all the responses is below 0.01, proving that the regression models are statistically significant and reliable. CV, VM, FC, and Ash . R^2 values suggest that the model describe experimental data variance of 97.5%. The Adeq. precision values of greater than 4 indicate that all four response models have fitted strongly (Jun, Abdul Raman, & Buthiyappan, 2020). Besides, the expected and actual response values are closely correlated, as shown in Figure 1, further verifying the high predictive accuracy of regression models. Analysis of variance (ANOVA) indicated that the four predictive models successfully capture data with reasonable accuracy.

4.5.1 Optimization of Refuse Derived Fuel formulation

Based on the models obtained and input criteria, the RDF from the hazardous industrial waste and biomass are formulated. Since predictive models are statistically validated, empirical algorithms were used to find the most desirable result (Buthiyappan et al., 2019). All parameters and responses with high and low limits are specified to identify the optimum condition. The RDF formulation was carried out based on the maximum efficiency for the parameters studied and the responses obtained. As shown in Table 4.12, the optimum combination is selected based on the CV, VM, FC, and ash content. The result showed that the optimum ratio of hazardous wastes to biomass with the maximum CV of RDF was 1:0.01. The calorific value of the RDF developed in this study is considerably higher than previously developed form municipal solid waste (Safwat et al., 2019).

The optimized composition of RDF was selected based on CV, availability of the waste and disposal fee. As shown in Table 4.11, the paint sludge percentage (D) was optimized at the highest possible level in RDF due to its high CV value, low moisture content, and ready availability in Malaysia. Besides, its high disposal cost also being one of the reasons for this selection. As stated earlier, RDF's production cost depends on the disposal cost paid by the industry, so since paint sludge is being the highest with their higher CV value, it's best to choose with higher % composition compared to others. It should also be stressed that the production costs of RDF are dependent on the waste disposal costs of the industry.

In RDF, palm oil sludge, synthetic rubber waste and wastewater treatment plant sludge accounted for a comparatively higher percentage. This is almost certainly caused by their abundance and their chemical properties, which is better suited for fuel development. Although natural rubber and synthetic rubber have a higher CV, the disposal fee for synthetic rubber is lower, and natural rubber should be bought. This will directly increase the production cost of the RDF. The biomass was kept at the lowest possible concerning the economic value, although they contain a high CV value. The selection of the weigh coefficient is vital to manage the overall production cost of the RDF.

The conditions 1 to 6 were chosen to determine the effects of varied raw waste material compositions on product such as CV, ash, volatile matter, carbon moisture content as well as heavy metal characteristics. RDF optimum condition 1 is chosen to investigate the emission characteristics of the cement kiln among them. The composition of RDF was selected based the economic point of view as well as the CV content. The amount of paint sludge in the RDF composition is higher than other hazardous waste due to its higher disposal charge and CV content. This will greatly reduce production costs.

Table 4.11: The component and its ratio of the simulated hazardous waste and biomass

Waste	**Unit**	**RDF 1**	**RDF 2**	**RDF 3**	**RDF 4**	**RDF 5**	**RDF 6**
A	%	13.9	0	5	5	5	5
B		12.4	0	5	5	5	-
C		11.6	25	20	30	15	25
D		47.9	20	10	10	10	10
E		3.0	5	5	-	5	-
F		3.1	10	10	10	5	10
G		6.7	10	5	10	15	15
H		0.3	5	5	10	10	20
I		1.0	20	10	10	20	-
J		0.1	5	25	10	10	15
CV	kJ/kg	18648	11844	13610	11924	13200	13300
Moisture							
VM	%	32.0	23.9	23.9	24.8	22.1	24.1
FC		40.0	58.9	57.9	54.9	59.5	54.9
Ash		28.0	18.2	18.2	20.4	18.4	21.0

4.6 Refuse Derived Fuel Characteristics

The chemical properties of RDF are very important in evaluating the alternative processing and recovery options and are measured in the following dimensions: proximate analysis, fusing point of ash, ultimate analysis and energy content. The most important factors for choosing alternative fuels used in the cement industry are moisture and calorific values. (Zieri & Ismail, 2019). The minimum calorific value of RDF is about 12, 552 to 14, 644 kJ/kg. Table 4.12 shows that RDF produced from this study contained a CV of 18,648 kJ/kg, comparable with the bituminous coal sample, 24,267 kJ/kg. The data in that Table 4.12 shows the CV content in RDF is lower compares to the coals. However, the CV obtained in this study using HWs and biomass is higher than RDF developed by Geogiopoulou and Lyberatos (2020) using municipal solid waste (Georgiopoulou & Lyberatos, 2018).

However, the RDF's moisture content was found to be higher than the coal, 25 %. This may be attributed to low efficiency in the drying process and the forms of the raw materials used, mainly in sludge forms. This required more attention as moisture content is one of the critical parameters, especially when it comes to waste alternative, as excess moisture can ruin the product's quality. However, the moisture content of the RDF is within the range with is below 30 %. On the other hand, the total ash content in the RDF was lower than coal, but both recorded a value below 30%. The high moisture content of fuels used in energy conversion plants hinders the ignition process, as it slows down the combustion steps (drying, volatilization, and oxidation) since it requires more drying time. Consequently, volatilization and oxidation are also impaired, thus reducing the burning rate and combustion efficiency. Therefore, there would be no need to dry the RDF with a view to greater fuel potential if the moisture content is lower.

Tanner proposes an incinerated solid waste combustion method based on the correlation between moisture, ash, and combustible material contents. The optimal fuel must then contain the highest possible amount of organic matter and the least amount of moisture and ash. It is critical to note that waste must adhere to the tanner diagram shown below to be self-combustible. According to Tanner triangle (Figure 4.1), ash must be less than 60%, the moisture content should also be below 50%, and the combustible material should be greater than 25% for the fuel to burn independently and waste is theoretically feasible for combustion without auxiliary fuel. In this sense, from the data obtained in this study, RDF samples evaluated in this work are potential fuels for combustion because they presented moisture, ash, and combustible material percentages within the limits established by Tanner.

The metal content of different composition of RDF was determined as shown in Table 4.12. It illustrates that the heavy metal content was below the limits set by European countries such as Finland, Italy, France, and the Netherlands for RDF emission. The RDF contained a high amount of Barium, Chromium, Copper, Lead, Nickel, and Zinc. This is because, Waste F, Wastewater Treatment Plant Sludge B contributed a higher amount of Barium, Chromium, Copper, Zinc, and Lead, while Waste A, Palm oil sludge has contributed to a higher amount of nickel. It is essential to evaluate the composition of CV for specific usage in any cement plant. The calorific value and heavy metal content of RDF were defined as the two primary indices for determining the quality of RDF.

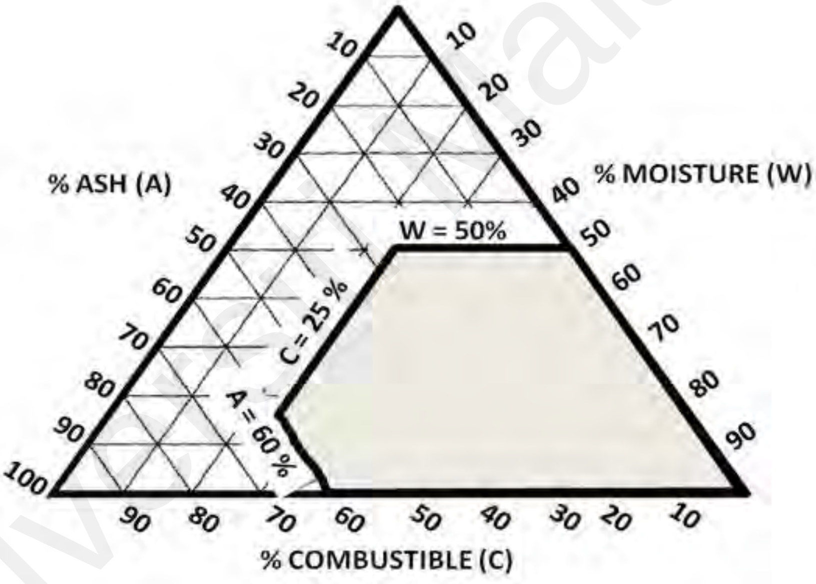


Figure 4.1: Tanner triangle for determining combustibility of waste components

The waste that collected from the selected industry in this study also does not content the herbicide, and pesticides, PCB. It has been proven form the analysis that's summarized in Table 4.13. If the waste content those elements the process of RDF will be challenging. Additionally, high PCB will cause the production of dioxin and furan during the burning process in the cement kiln. Therefore, the material without the content of PCB is selected in this study.

Figure 4.2: Powdered RDF developed in this study

Table 4.12: Characteristic of heavy metals content in the RDF

Heavy metals	TTLC Values	WAC Aternative Fuel (max)	Co-Processing Guidelines	RDF Specification	Coal	RDF 1	RDF 2	RDF 3	RDF 4	RDF 5	RDF 6
Lead	1,000	5,900	10000	300	<0.01	7	185.3	185.5	22.88	<0.01	134
Chromium	2,500	1,000	-	750	<0.01	20	33.81	92.7	3.53	71.66	32.23
Arsenic	500	3500	-	150	<0.01	<0.01	0.08	0.13	<0.01	<0.01	<0.01
Stanum	-	3,400	-	1,000	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Selenium	100	180	-	30	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nickel	2,000	30,000	-	600	<0.01	236	119.8	135.2	373.69	120.2	242.6
Tellurium	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cobalt	-	-	-	2,400	<0.01	<0.01	43.4	58.8	0.91	0.72	55.5
Vanadium	8,000	-	-	1,000	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Antimony	2,400	24,000	-	150	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Manganese	500	1,800	-	-	-	10.0	262.2	682.2	233.6	241.2	14.52
Chlorine	-	6000	2 %	1000	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fluorine		-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Bromides		-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Iodin		-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	2500	13000	30000	750	<0.01	<0.01	412.7	534.1	319.5	60.59	16.93
Zinc	5000	80000	30000	2500	212.1	1289	1999.0	1829.4	1138.9	1395.6	195.0
Mercury	20	15	10	6	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 4.12 (continued)

Heavy metals	TTLC Values	WAC Aternative Fuel (max)	Co-Processing Guidelines	RDF Specification	Coal	RDF 1	RDF 2	RDF 3	RDF 4	RDF 5	RDF 6
Zirconium	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cadmium	100	1800	-	30	<0.01	<0.01	0.48	6.56	<0.01	<0.01	<0.01
Thallium	700	-	-	210	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Barium	10, 000	74, 500	-	3,000	2.6	<0.01	301	<0.01	34.82	379.7	25.31
Strontium	-	-	-	-	-	-	47.91	<0.01	35.57	36.69	25.31
Molybdenum	3,500	9, 500	-	1,050	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Beryllium	75	-	-	22.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium – VI	500	-	-	150	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Argentum	500	-	-	150	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 4.13: SVOC, herbicide, volatile organics, pesticides, PCB content of RDF compared with TTLC values

Types	**Analysis**	**TTLC Values (ppm)**	**RDF 1**	**RDF 2**	**RDF 3**	**RDF 4**	**RDF 5**	**RDF 6**
SVOC	Pentachlorophenol	17	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Herbicide	2,4-Dichlorophenoxy acetic acid	100	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	2,4,5-Dichlorophenoxypropionic acid	10	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Volatile organics	Trichlroethylene	2,040	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pesticides & PCB	Aldrin	11.4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Chlordane	2.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	DDT	1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	DDE	1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	DDD	1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Dieldrin	8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Endrin	0.2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Heptachlor	4.7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

RDF meets acceptance criteria of selected cement plant at based on result obtained, any increment to the total loading of ash content to the Electrostatic Precipitator (EP) will be insignificant when RDF used to substitute coal as fuel. A trial run using RDF in the cement plant was subsequently arranged to determine the performance of RDF in an operating environment. The CHNOS properties as well as the physical properties of RDF such as ignitability and flammability of the RDF were also studied and summarized in the Table 4.14 and 4.15

Table 4.14: CHNOS Properties

CHNOS	**Units**	**RDF**					
		1	**2**	**3**	**4**	**5**	**6**
Carbon	%	59.0	51.2	48.4	52.0	51.2	51.3
Hydrogen	%	6.0	6.2	8.3	5.2	4.4	4.5
Nitrogen	%	3.0	3.2	2.8	3.1	3.2	3.2
Oxygen	%	12.0	18.3	17.9	15.9	30.2	17.1
Sulphur	%	0.61	2.3	2.2	2.3	2.1	2.4
Chlorine	%	1.6	1.6	2.1	1.0	0.56	0.5

Table 4.15: Ignitability and Flammability

Parameter	**RDF**					
	1	**2**	**3**	**4**	**5**	**6**
Flammability	All the RDF Not burning					
Ignitability	All the RDF Not burning					

4.7 RDF usage in the cement plant

The selected cement manufacturing industry has carried out clinker production using different RDF ratios. Condition 1 was selected for the testing in the cement plant. 1000 tons of RDF were used and it was demonstrated that RDF produced in this work meets the requirement and can be safety used as a supplementary fuel to coal without any adverse effect to environment. Besides that, it also to justify the utilization of RDF in cement industries as a safe and economically viable supplementary fuel to coal. The analysis was conducted to review compliance against the product specification as well as other parameters listed in the TTLC requirements. Table 4.16 shows the Chemical and Physical Characteristics of RDF used in the cement kiln.

Table 4.16: Chemical and Physical Characteristics of RDF used for the emission analysis

Parameter	Unit	Details
State	-	Solid
Colour	-	Brownish to dark grey
Odor	-	None to slight
Solubility in water	-	Insoluble
pH	-	6.3 – 7.4
Reactivity	-	React exothermally with strong oxidizers
Stability	-	Stable under normal handling
Density	kg/m^3	900 – 1100
Calorific value	MJ/kg	12.55
Moisture content	%	20
Volatile matter	%	30
Ash content	%	25
Carbon, C	%	59
Hydrogen, H	%	6
Nitrogen, N	%	3
Sulfur, S	%	0.61
Oxygen, O	%	12
Chlorine, Cl	%	1.6
Antimony	ppm	150
Cuprum	ppm	750
Lead	ppm	300
Chromium	ppm	750

Table 4.16 (continued)

Parameter	Unit	Details
Arsenic	ppm	150
Stanum	ppm	1000
Selenium	ppm	30
Nickel	ppm	600
Cobalt	ppm	2400
Fluorine	ppm	20000
Bromides	ppm	20000
Iodine	ppm	20000
Zinc	ppm	5000
Mercury	ppm	8
Cadmium	ppm	30
Thallium	ppm	250
Barium	ppm	3000
Molybdenum	ppm	1000
Berylium	ppm	25
Chromium VI	ppm	150
Argentum	ppm	150
Vanadium	ppm	1000

4.7.1 Emission Evaluation of RDF in The Cement Plant

The purpose of this monitoring is to measure concentrations of dust particulates, heavy metals and gaseous pollutants in the flue gases of chimneys leading from cement production processes by using RDF as a coal substitute. Tabel 4.17 and 4.18 summarized summary of monitoring program and detil of stack used in this study. This complies with the limits stipulated under the Environmental Quality (Clean Air) Regulations, 1978. One (1) chimney leading from cement production processes was monitored for dust particulate concentrations in their flue gases using isokinetic sampling technique according to Malaysian Standard 1596, 2003. At the same time, concentrations of nitrogen dioxide and heavy metals in the flue gas of main chimney was also measured according to the methods.

Table 4.17: Summary of Monitoring Program

Stack	Source description	Parameters Tested
S3	Main chimney (During RDF Firing)	Dust Nitrogen dioxide Heavy metals - Hg - Pb - Cr - Cu - Cd - Sb - As

Table 4.18: Detail of Stack

Items	Stack
Type of installation	Main Chimney – EP (Raw Mill & Preheater)
Stack Height	100.7 meter
Stack Diameter (at test point)	4.0 meter
Sampling Point (from ground level)	38.3 meter
Operation Condition:	
Hours of operation	15.75 hours
Capacity during sampling	316.06 ton / hr
Exhaust Fan Speed	591 rpm
Dust Control System	EP

Distance of sampling points for each sampling line in the chimneys (round shape) determined based on MS 1596, 2003 (in meter) are shown in the Table 4.19.

Table 4.19: Detail of stationary sources

Point	Distance of sampling points from the inner stack wall, m
1	0.10
2	0.31
3	0.55
4	0.86
5	1.30
6	2.50
7	2.94
8	3.25
9	3.49
10	3.70

This sampling is conducted by withdrawing flue gas sample from the stack isokinetically. Dust particulate in the sampled flue gas is detained and collected by means of filtration. The sampling point or port-hole of test chosen is located at a place where the flue gas flow is comparatively uniform, avoiding any turning corner. This is essential to avoid any turbulent effects and a uniform gas flow is measured. An ideal point will be a distance at least five (5) times the internal diameter of the stack from the flue inlet point.

This study aims to confirm the usability of generated RDF as an alternative for bituminous coal in the selected cement manufacturing industry. The study conducted by (Kara, 2012) shows that the maximum net saving can be obtained by adding 15 % of the RDF as an additional fuel in cement production does not harm the quality of the clinker and gas emission values. Table 4.20 shows the three various conditions used in this study. The potential environmental benefits and effects of substituting the RDF for the coal in the selected cement plants were also evaluated. Actual trial runs were conducted for three months in the chosen cement plant, where 5 MT/hour

(13 %), 8 MT/hour (23 %) of RDF is fed into the rotary kiln substituting the coal, via a separate feeding line, based on two different conditions. Although the production of RDF affects the environment through the consumption of energy and fuel, the substitution of RDF in cement manufacturing can reduce the emission and help in energy recovery.

Table 4.20: RDF usage in the case studied cement plant

Condition	**Rate of RDF (tons/hour)**	**Rate of Coal (tons/hour)**
1	0 (100% of coal)	25.7
2	5	21.8
3	8	19.5

Table 4.21 and Figure 4.3 to Figure 4.9 shows the gas emission results of RDF based on the conditions used in this study. The result revealed that the quantity of NOx using RDF in both cases remained within the standard limits, which is below 800 mg/ Nm^3. As shown in Table 4.21, the emission of NO_X was higher when the 8 tons/hour of RDF is used compared to when 5 tons/hour of RDF is used. The emission of NO_X reduced from 356 mg/ Nm^3 to 301 mg/ Nm^3 when 8 tons/hour of RDF is substituted in the coal. Nitrogen oxides in the rotary kiln are made up of 90% NO and 10 % of NO_2. Cement manufacturing is facing a challenge as the NO formation increases exponentially with the temperature. Even a small change above 1400 ^{0}c gives a more significant impact on the concentration of NO_X with oxygen. The cement kiln temperature is between 200 and 1600 ^{0}C, which is around the same as the temperature of the threshold for the formation of thermal NO_X.

It should be emphasized that the mechanism to control the emission of NOx and SOx are more complex in cement plant as it depends on other factors such as lime, iron ores, sandstones, coal and other additives besides RDF. As shown in Table 4.21, apart from SO_X, all other parameters complied with the emission standards. All three conditions have emitted a higher amount of SO_X and exceed the standard limit, including when 100 % of coal is used. The highest SO_X emission of 765 mg/ Nm^3 is reported when 100 % of coal used, and the lowest emission of 487 mg/ Nm^3 when 5 ton/hour of RDF is replaced in the cement kiln. The addition of 5 tons/hour and 8 tons/hour of RDF to the primary fuel reduced the SO_X amount, although it did not comply with the standard limit. It should be emphasized that the cement plant used in this study receiving limestones from the quarry contains sulphur more than 2%. So the higher amount of SO_X possibly contributed by the geological formation of the deposits of limestone and not from the RDF or the coal alone. However, this problem is prevalent based on historical stack monitoring data and by installing selective catalytic regeneration and flue gas desulfurization techniques. This would incur additional installation costs, but gate fees and revenues may compensate. Besides, the amount of NO_X and SO_X should be kept within the limit by controlling the waste acceptance criteria (refer to Table 4.2).

Besides, the emission of heavy metals, including Zinc, Arsenic, Lead, Copper, Antimony, and Chromium, shows various ranges of concentration in the raw samples. In both situations, the heavy metals concentration was lower than the country's limit. This revealed that the usage of RDF in the kiln operation does not affect the emission quality. Calorific value for the incoming HW's was limited to 300kcal/kg to ensure that only product with calorific value will be selected to be use in the manufacturing process. Meanwhile, sulphur content is limited to 1.5% - lower than the Fuel acceptance Criteria, requirements to ensure compliance after the manufacturing process.

Table 4.21: Combustion gas emission results of RDF based on the conditions used

Parameter (mg/ Nm^3)	**Coal**	**5 MT/h RDF**	**8 MT/hr RDF**	**Co-processing guidelines**	**Clean Air Regulations (CAR)**	
					1998	**2014**
Dust	31.9	27.8	34.8	50	-	-
Nitrogen Oxides	295	326	301	800	2,000	800
Sulphur dioxide	761	487	835	400	200	10
Hydrogen	2.5	2.3	2.9	10	-	-
Volatile Organic Compound	7	9	9	20	-	-
Chlorine	2	4	3.5	200	-	-
Mercury	< 0.01	< 0.01	< 0.01	0.05	10	0.005
Cadmium	< 0.01	< 0.01	< 0.01	<0.05	15	-
Thallium	< 0.01	< 0.01	< 0.01	<0.05	-	-
Zinc	3.8	4.8	2.6	100	100	-
Hydrogen Fluoride	< 0.1	< 0.1	< 0.1	1	-	-
Dioxin & Furan (ng/m^3)	ND	ND	ND	0.1	-	-
Arsenic	< 0.01	< 0.01	< 0.01	Total 2.5	25	-
Cobalt	< 0.01	< 0.01	< 0.01		-	-
Lead	< 0.01	< 0.01	< 0.01		25	-
Copper	< 0.1	< 0.1	< 0.1		100	-
Antimony	< 0.01	< 0.01	< 0.01		-	-
Chromium	< 0.01	< 0.01	< 0.01		-	-
Nickel	0.5	0.8	0.3		-	-
Vanadium	< 0.5	< 0.5	< 0.5		-	-
Manganese	< 0.1	< 0.1	< 0.1		-	-

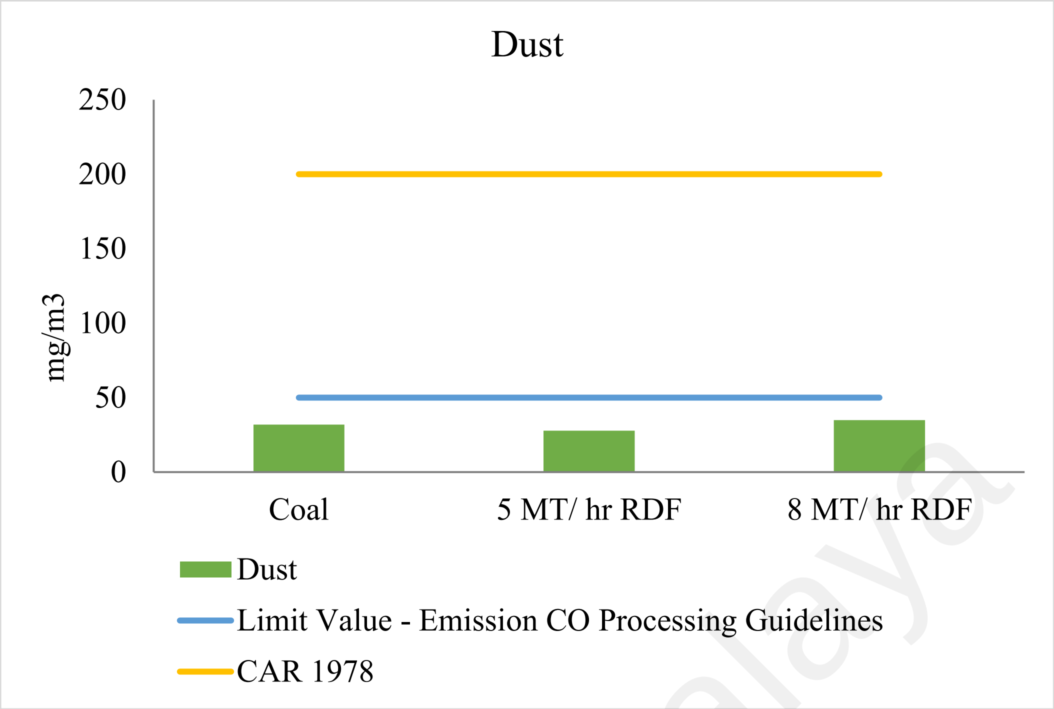


Figure 4.3: Emission of Dust in comparison with Emission CO processing guidelines

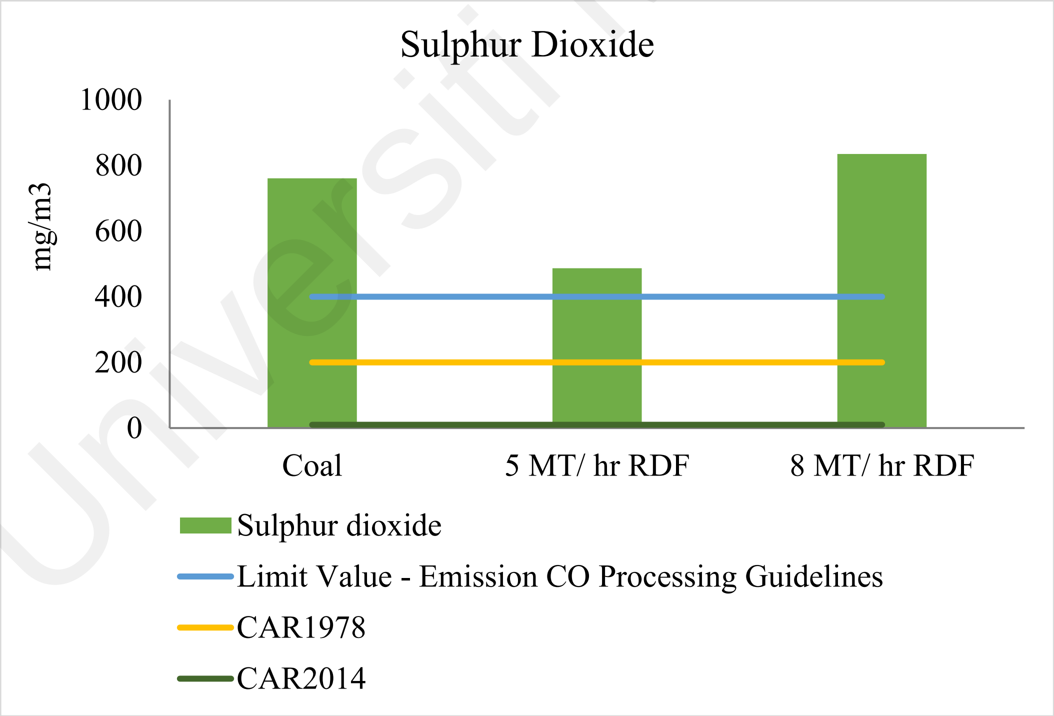


Figure 4.4: Emission of SO_x in comparison with Emission CO processing guidelines, CAR 1978 and CAR 2014

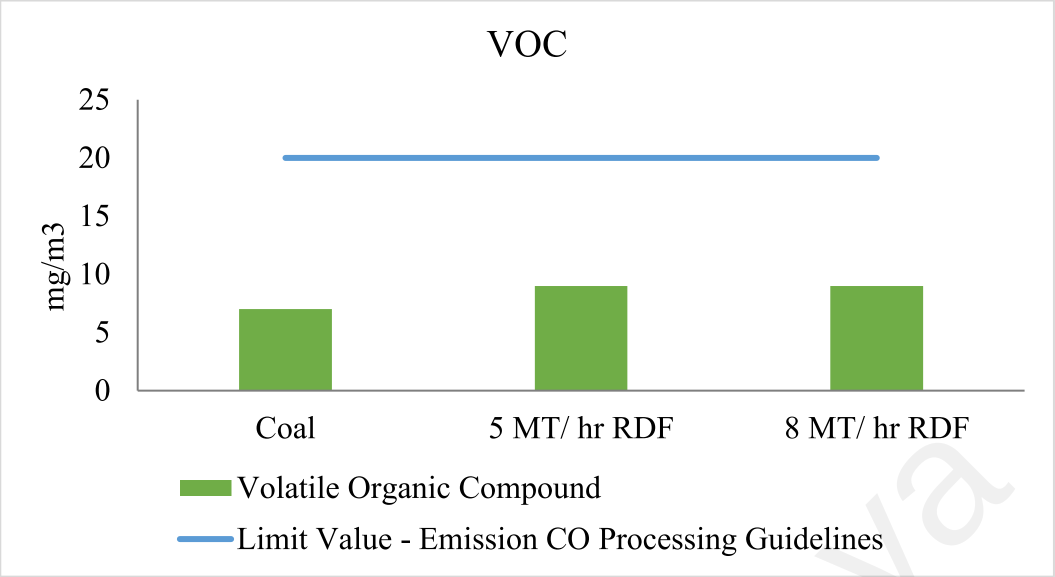


Figure 4.5: Emission of volatile organic compound in comparison with Emission CO processing guidelines

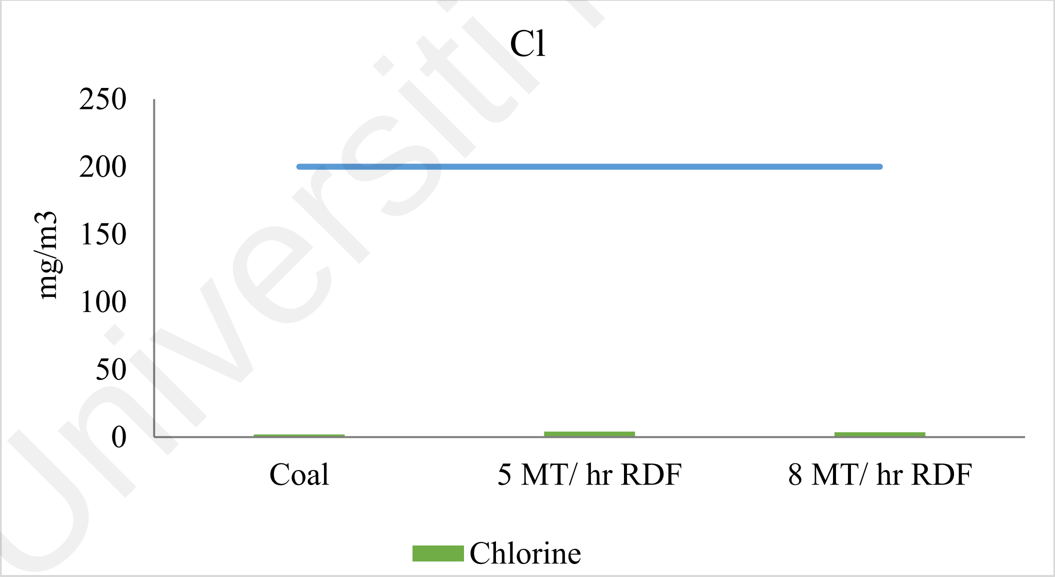


Figure 4 6: Emission of chlorine

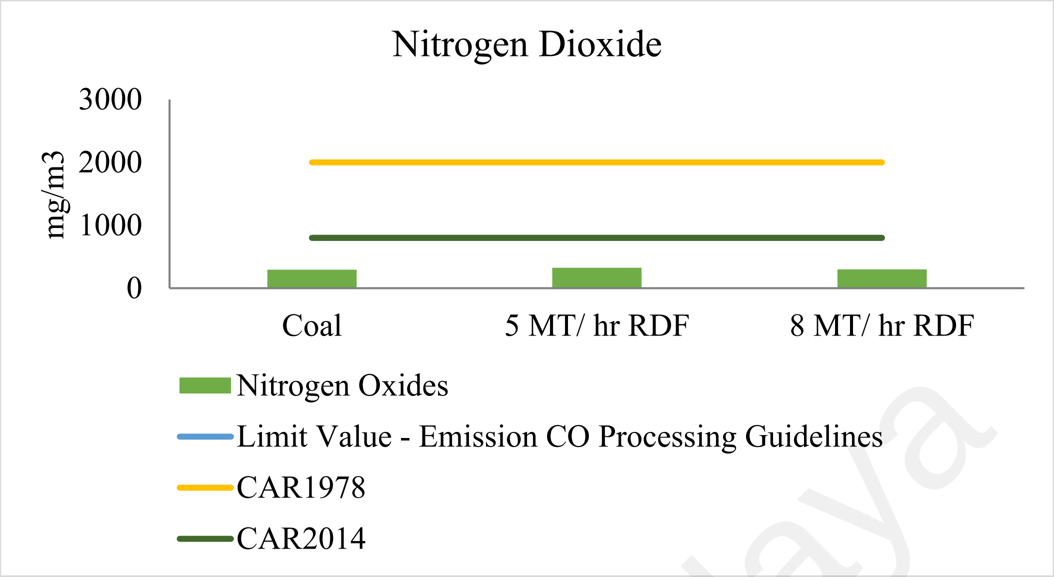


Figure 4.7: Emission of NO_x in comparison with Emission CO processing guidelines, CAR 2014

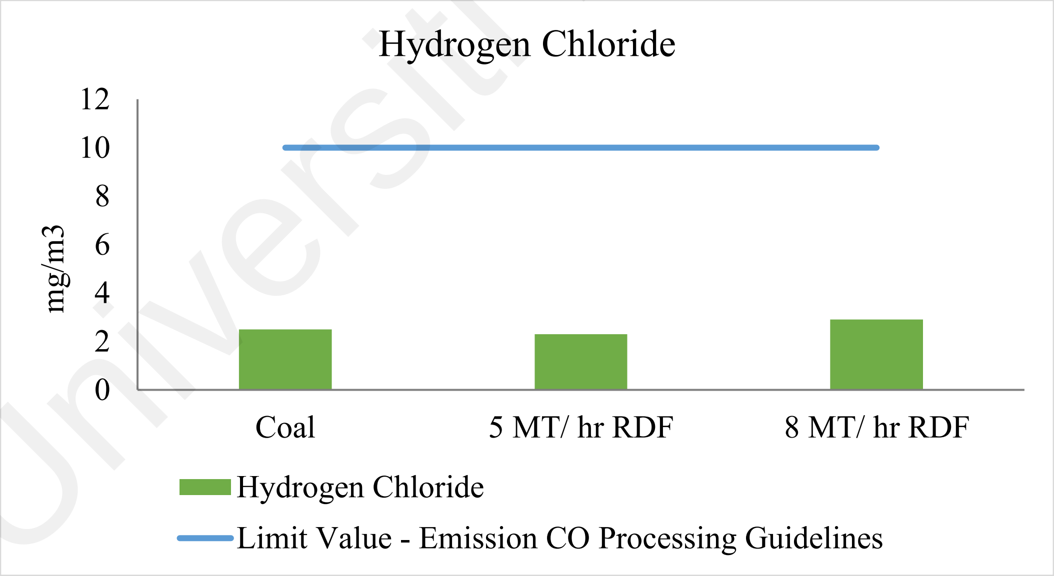


Figure 4.8: Emission of hydrogen peroxide in comparison with Emission CO processing guidelines

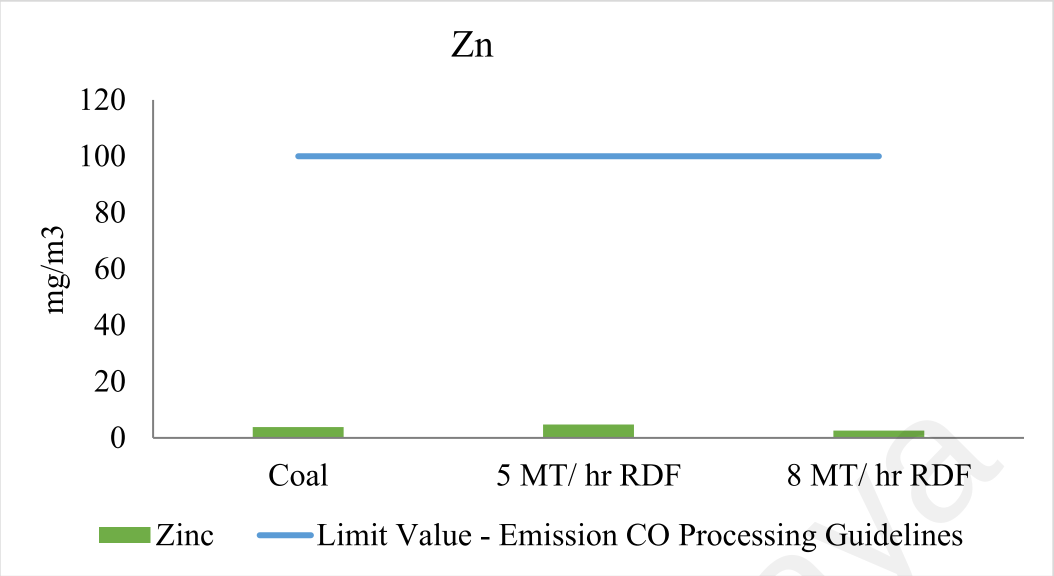


Figure 4.9 : Emission of zinc in comparison with Emission CO processing guidelines

4.8 Clinker quality

Clinker quality is another important economic aspect in determining the viability of using RDF developed in the study at the selected cement kiln. For both reliability and economic purposes, it is vital to ensure that the product generated by the selected cement manufacturing plant is not harmed in any way using RDF. Cement clinker quality parameters were measured by offline laboratory analysis by using X-RAY analyzer. Table 4.22 to Table 4.23 and Figure 4.10 to Figure 4.28 shows the clinker quality parameters monitored by the cement plant in determining the quality of the clinker produced for 7 days of trial using the coal as well as the optimized RDF recipe (1000 MT). In addition, Figures 4.12 to 4.30 provide the clinker quality characteristics for coal and RDF in graphical form representing the valued stated in Table 4.22 and Table 4.23. The Figures Based on the result obtained, it can be concluded that the usage of RDF and at the production limit of 5MT/hr, the clinker quality were within the stipulated acceptable range and almost the similar to the coal.

The clinker produced in the rotary kiln determines the cement's durability and strength. Clinker quality is determined by parameters amount such as lime saturation factor (LSF), silica moduli (SM), alumina moduli (AM), and alite (C3S), as listed in the Table 4.24. The rotary kiln heats the raw meal to high temperatures, where the various compounds react with one another. Lime (CaO) reacts with components in the raw meal, such as silica, alumina, and iron oxide, to form dicalciumsilicate (C_2S), tricalciumsilicate (C_3S), tricalcium aluminate (C_3A), and tetracalciumaluminoferrite complexes (C_4AF). These reactions result in the formation of clinker, a nodular material. To maintain product quality, all of these components must be present in the clinker in the proper proportions. Unreacted lime appears in the clinker as free lime and should be kept to a minimum.

The major parameters that define the clinker's quality in the chemical analysis of cement are the lime saturation factor (LSF), silica moduli (SM), and alumina moduli (AM), and others. LSF is the ratio of actual lime to the theoretical lime required by the clinker's other major oxides. LSF greater than 100% indicates that some free lime is present in the clinker. For technical purposes, a good LSF value is between 80% and 95% (Aldieb & Ibrahim, 2010). Silica moduli (SM) is the proportion of SiO2 to the total of Al_2O_3 and Fe_2O_3 present in the clinker. Increased silica moduli reduce clinker burnability by reducing liquid phase content and the potential for coating to form in the kiln. SM should be in the range of 1.9 To 3.2 which is in line with data obtained for RDF. Increasing the SM also causes the cement to take longer to set and harden. AM characterizes the clinker by the proportion of alumina to iron oxide and determines the composition of liquid phase in the clinker. If AM is less than 1.5, both oxides will be present in their molecular ratios, allowing only tetracalcium aluminoferrite to develop in the clinker, consequently, the clinker do not contain tricalcium aluminate (Alemayehu & Sahu, 2013). This scenario caused low heat of hydration, slow setting. AM less than 2.5 and greater than 1.5, according to the results as can be seen in Table 4.25. The amount of unreacted lime in the clinker is measured as free lime

(FCaO), and the lesser the free lime, the closer the reactions are to completion. However, a low level of free lime can imply a burn that is extremely hard and costly. The RDF contains free lime in the desired amount (Table 4.23).

Table 4.22: Clinker quality analysis using coal

	Max.	**Mix.**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**
Coal									
LOI	0.43	0.02	0.33	0.26	0.33	0.21	0.11	0.11	0.34
SiO_2	22.94	19.98	21.21	21.42	21.34	20.93	21.58	21.78	21.22
AIO_2	5.37	4.02	4.48	4.12	4.32	4.36	4.59	4.76	4.48
Fe_2O_3	4.51	2.61	3.34	2.99	3.03	3.26	3.26	3.43	3.39
CaO	70.21	66.03	67.99	68.58	68.23	68.20	67.49	67.16	67.88
MgO	2.31	0.06	0.96	0.99	0.96	0.99	1.08	1.10	0.98
SO_3	1.75	0.34	1.12	1.08	1.11	1.34	1.22	1.11	1.14
K_2O	0.69	0.31	0.51	0.50	0.60	0.60	0.52	0.44	0.52
FCaO	7.11	0.45	1.34	1.57	1.57	3.80	0.86	1.44	2.64
LSF	107.43	93.23	101.71	102.69	102.11	103.54	99.31	97.57	101.46
SM	3.12	2.14	2.71	3.01	2.90	2.75	2.75	2.66	2.70
AM	1.68	1.08	1.34	1.38	1.43	1.34	1.41	1.39	1.32
C_3S	81.3	51.94	75.22	78.01	75.79	69.11	71.7	65.09	69.33
C_2S	21.71	-2.04	4.06	2.56	4.00	7.87	7.78	7.78	8.53
C_3A	7.96	4.63	6.22	5.86	6.32	6.04	6.65	6.81	6.14
C_4AF	13.72	7.94	10.16	9.10	9.22	9.92	10.44	10.32	10.32
LP	27.35	19.92	22.32	20.47	21.21	21.87	22.66	23.49	22.45
F-CaO	6.77	0.77	1.37	1.73	1.68	2.69	1.23	1.9	1.83
L/W	1408	1071	1248	1134	1228	1232	1236	1230	1273

Table 4.23: Clinker quality analysis using 5 MT/hour RDF

	Max.	**Min.**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**
					5MT/hour RDF				
LOL	0.43	0.02	0.25	0.18	0.16	0.33	0.18	0.12	0.39
SiO_2	22.94	19.98	21.33	21.18	21.45	21.32	20.99	21.10	20.57
AIO_2	5.37	4.02	4.76	4.66	4.81	4.77	4.62	4.60	4.71
Fe_2O3	4.51	2.61	3.50	3.50	3.54	3.57	3.52	3.60	3.45
CaO	70.21	66.03	67.76	67.71	67.47	67.27	68.12	67.67	66.77
MgO	2.31	0.06	0.91	1.00	1.06	1.00	1.04	0.49	1.58
SO_3	1.75	0.34	0.89	1.11	0.95	1.06	0.85	0.97	1.16
K_2O	0.69	0.31	0.54	0.58	0.48	0.48	0.60	0.55	0.63
FCaO	7.11	0.45	1.57	2.33	2.67	2.20	2.38	0.90	1.28
LSF	107.43	93.23	100.21	100.94	99.17	99.45	102.42	101.23	102.10
SM	3.12	2.14	2.58	2.60	2.57	2.56	2.58	2.57	2.52
AM	1.68	1.08	1.36	1.33	1.36	1.34	1.31	1.28	1.37
C_3S	81.3	51.94	70.33	68.84	63.36	65.68	71.99	75.37	73.66
C_2S	21.71	-2.04	8.10	8.79	13.70	11.58	5.87	3.64	3.40
C_3A	7.96	4.63	6.69	6.43	6.76	6.60	6.29	6.10	6.64
C_4AF	13.72	7.94	10.65	10.65	10.77	10.86	10.71	10.95	10.50
LP	27.35	19.92	23.48	23.32	23.85	23.72	23.25	22.90	24.05
F-CaO	6.77	0.77	1.54	2.02	2.76	1.72	2.12	1.31	0.89
L/W	1408	1071	1298	1287	1260	1285	1256	1258	1302

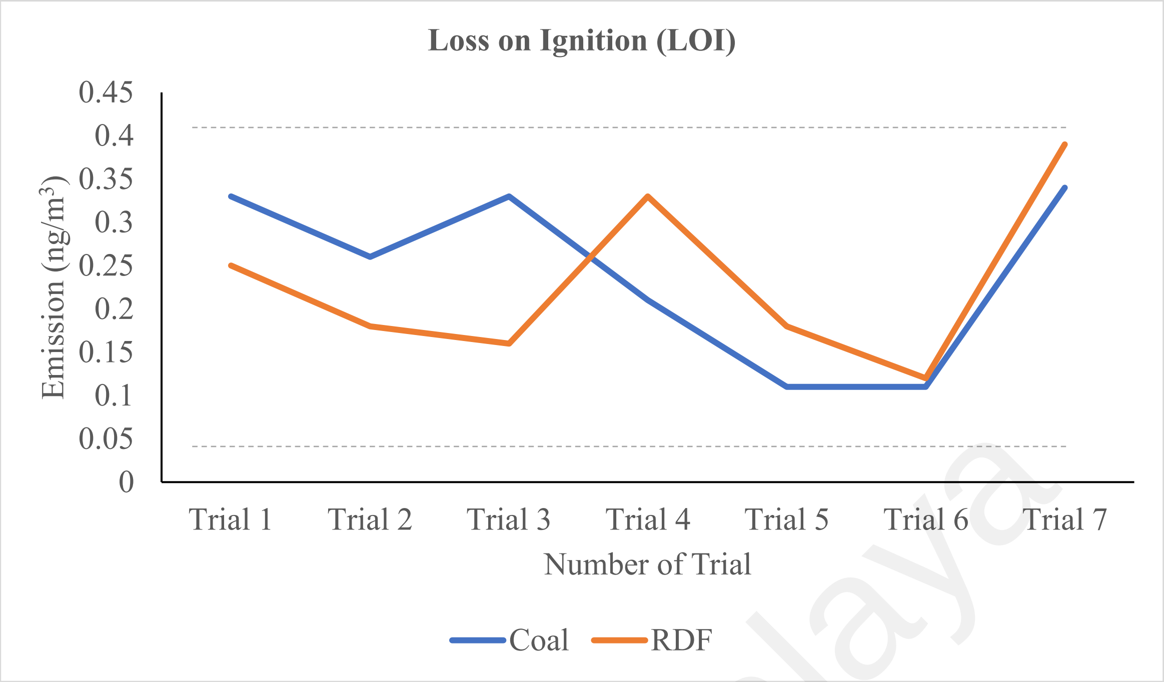


Figure 4.10: Lost on ignition during co-combustion of coal and 5 MT/hour of RDF

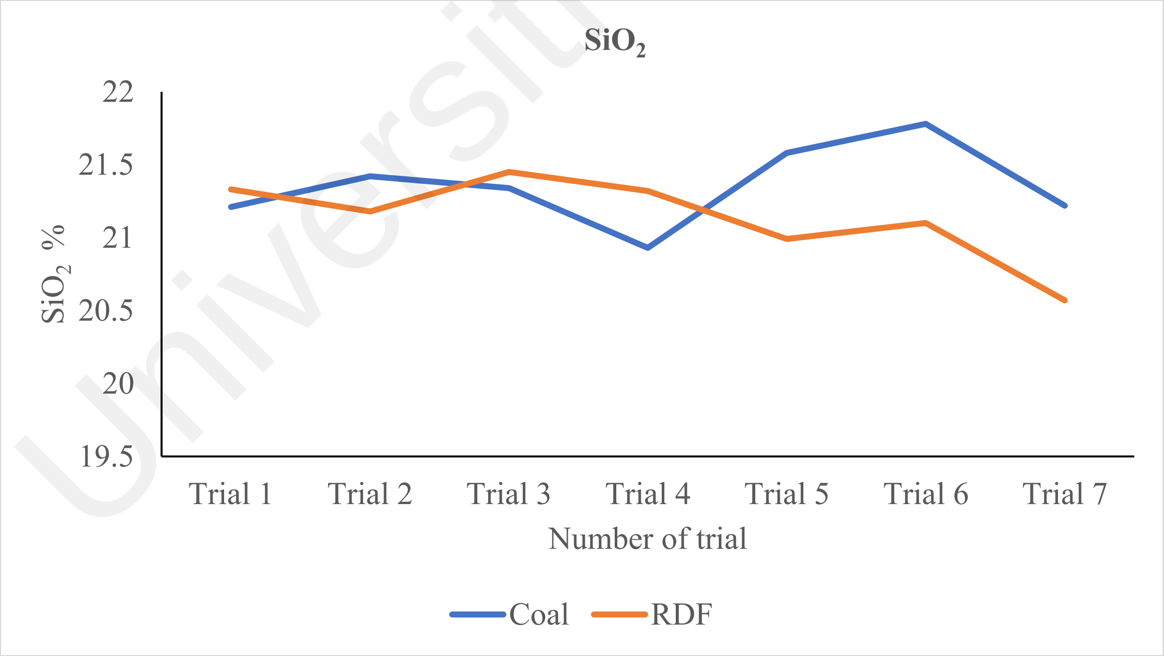


Figure 4.11: SiO_2 during co-combustion of coal and 5 MT/hour of RDF

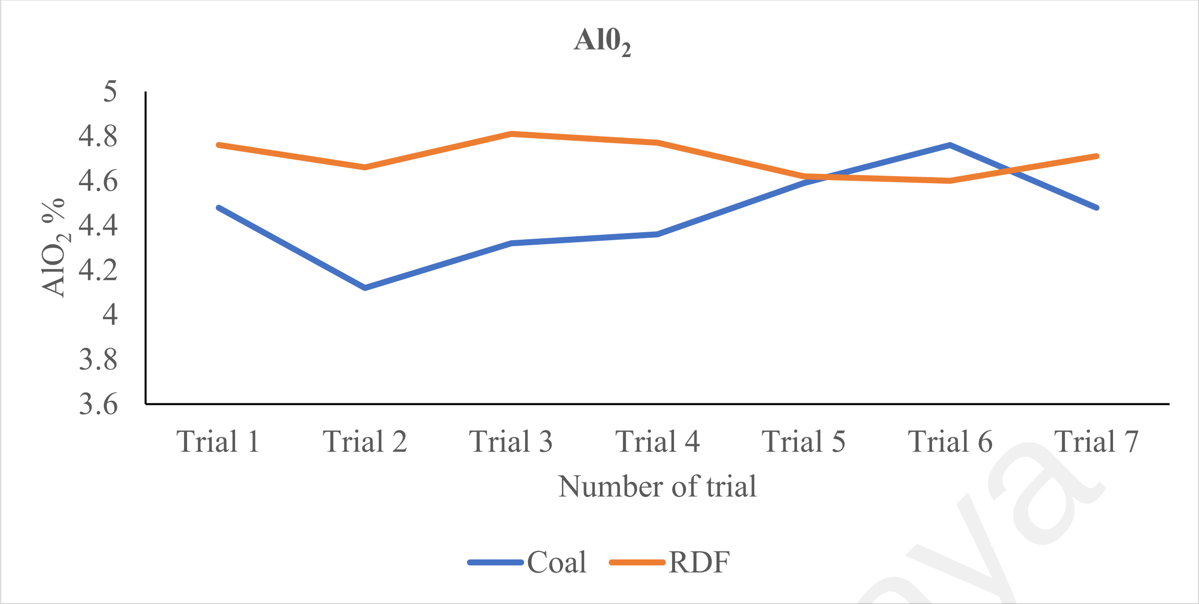


Figure 4.12: AIO$_2$ during co-combustion of coal and 5 MT/hour of RDF

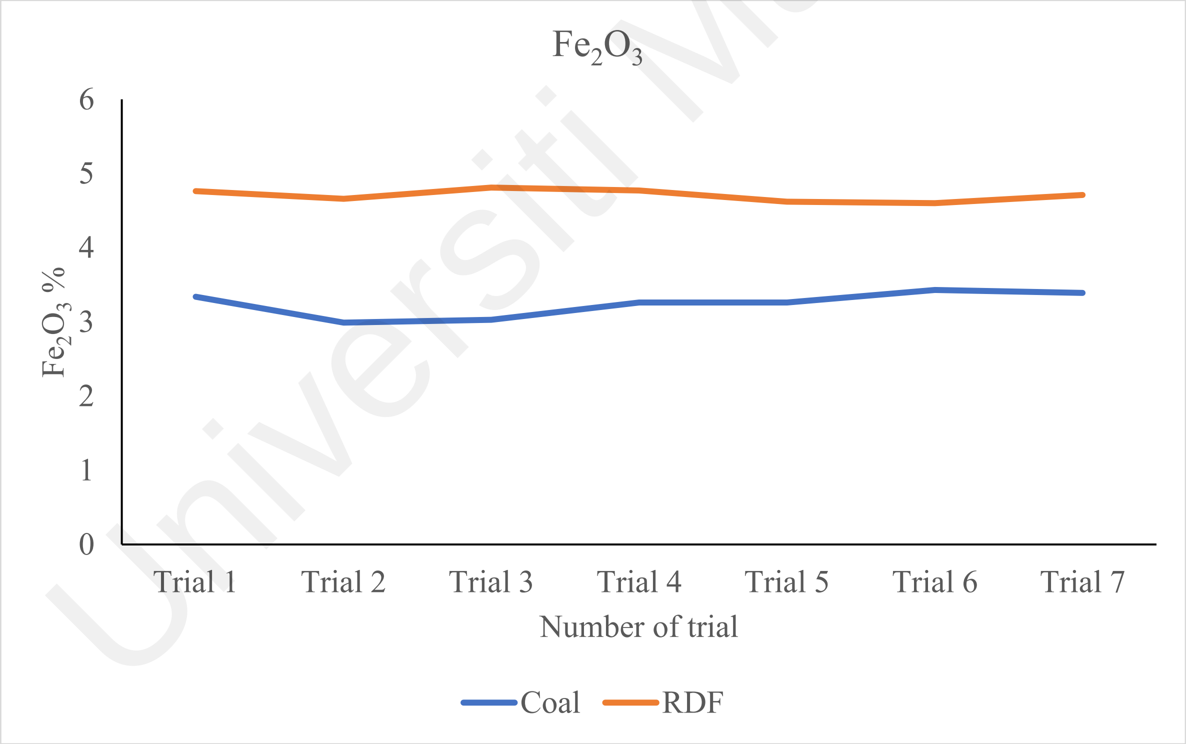


Figure 4.13: Fe$_2$O$_3$ during co-combustion of coal and 5 MT/hour of RDF

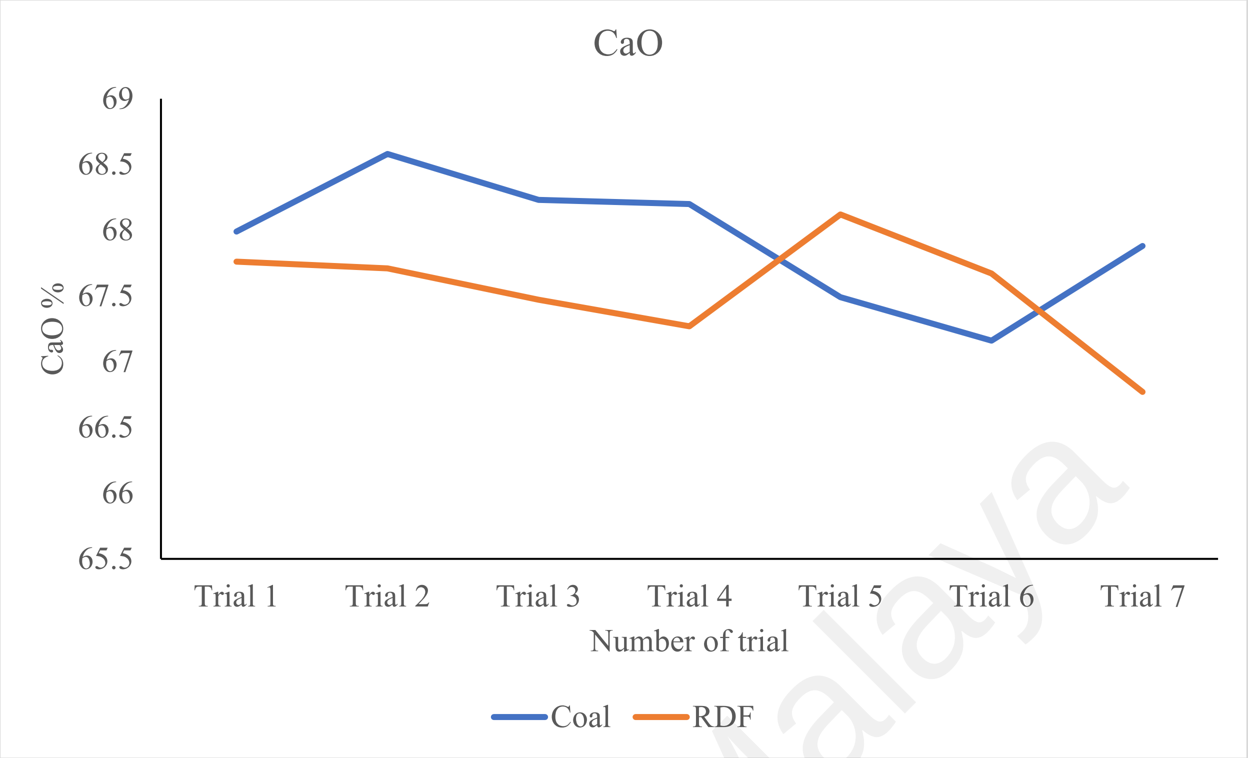


Figure 4.14: CaO during co-combustion of coal and 5 MT/hour of RDF

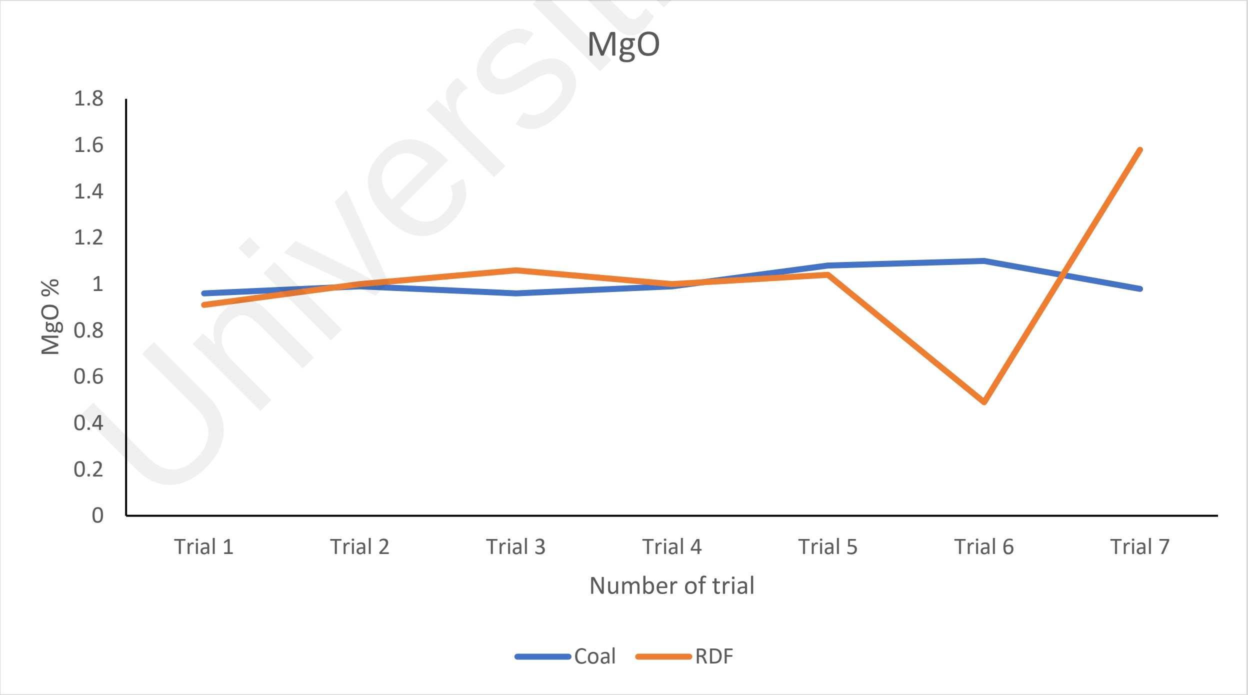


Figure 4.15: MgO during co-combustion of coal and 5 MT/hour of RDF

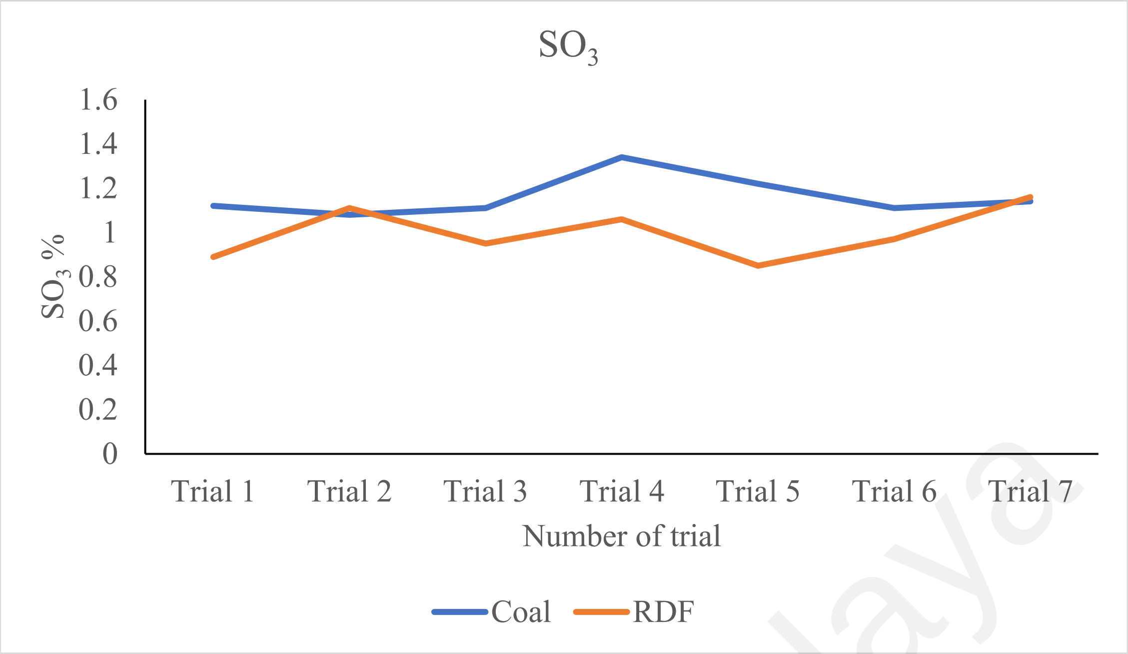


Figure 4.16: SO_3 during co-combustion of coal and 5 MT/hour of RDF

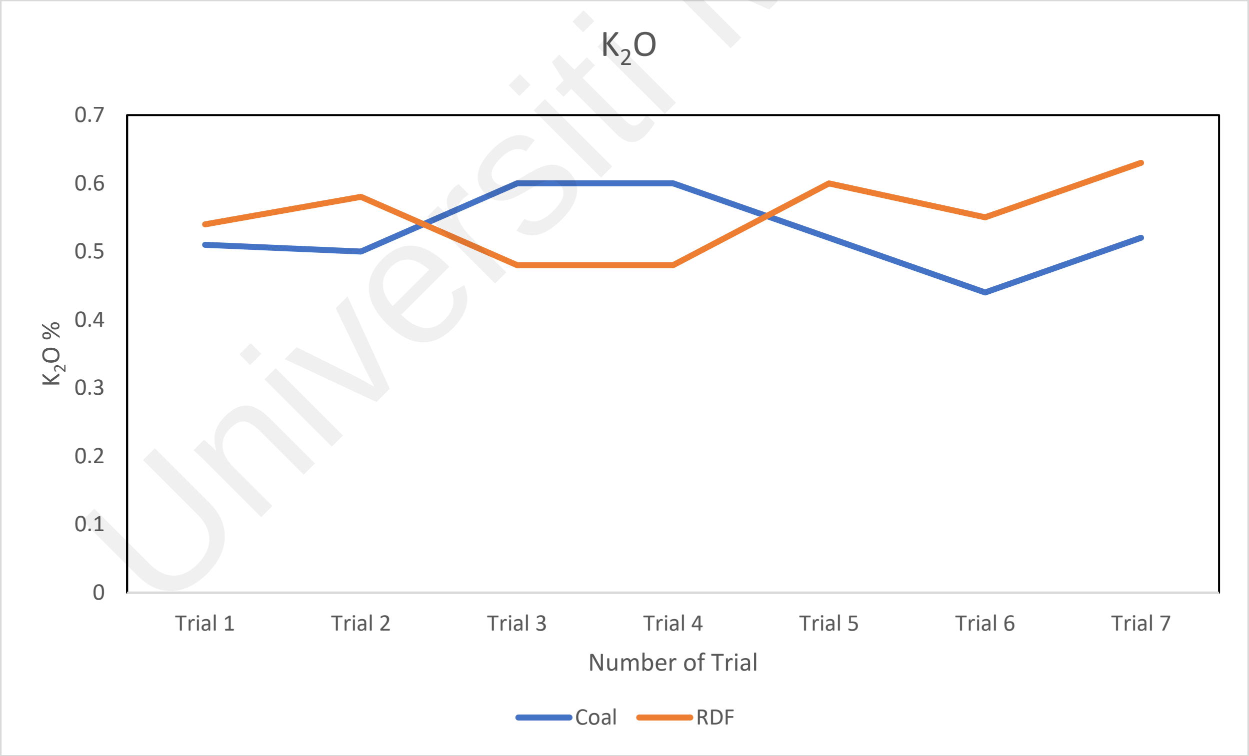


Figure 4.17: K_2O during co-combustion of coal and 5 MT/hour of RDF

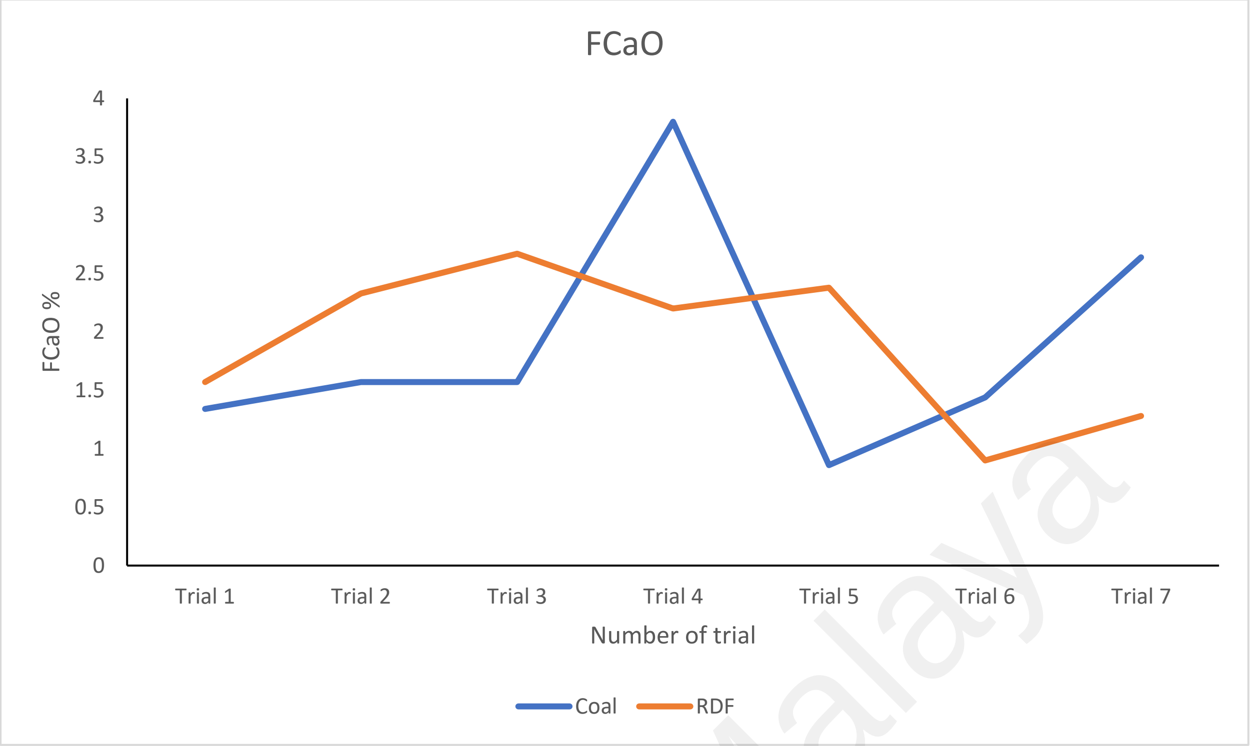


Figure 4.18:FCaO during co-combustion of coal and 5 MT/hour of RDF

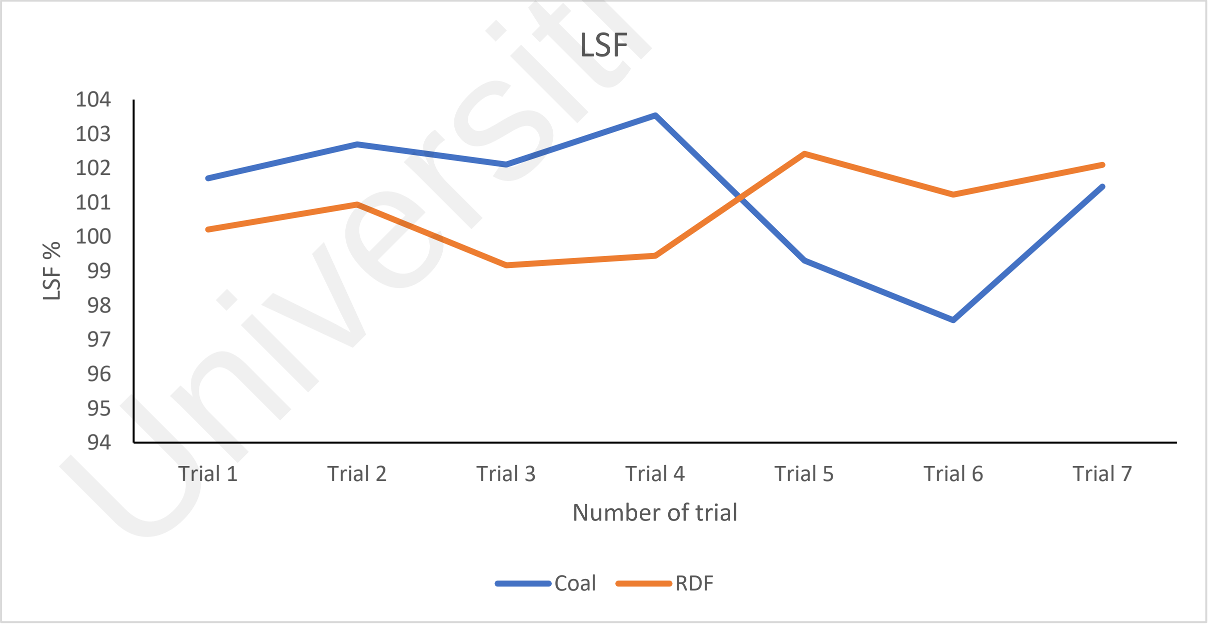


Figure 4.19: LSF during co-combustion of coal and 5 MT/hour of RDF

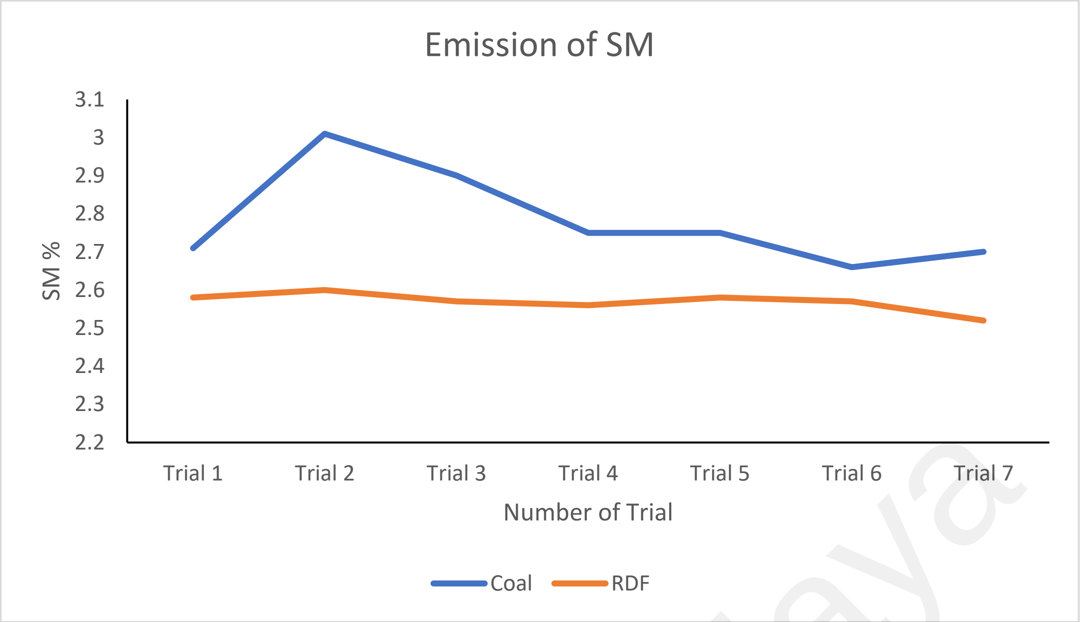


Figure 4.20: SM during co-combustion of coal and 5 MT/hour of RDF

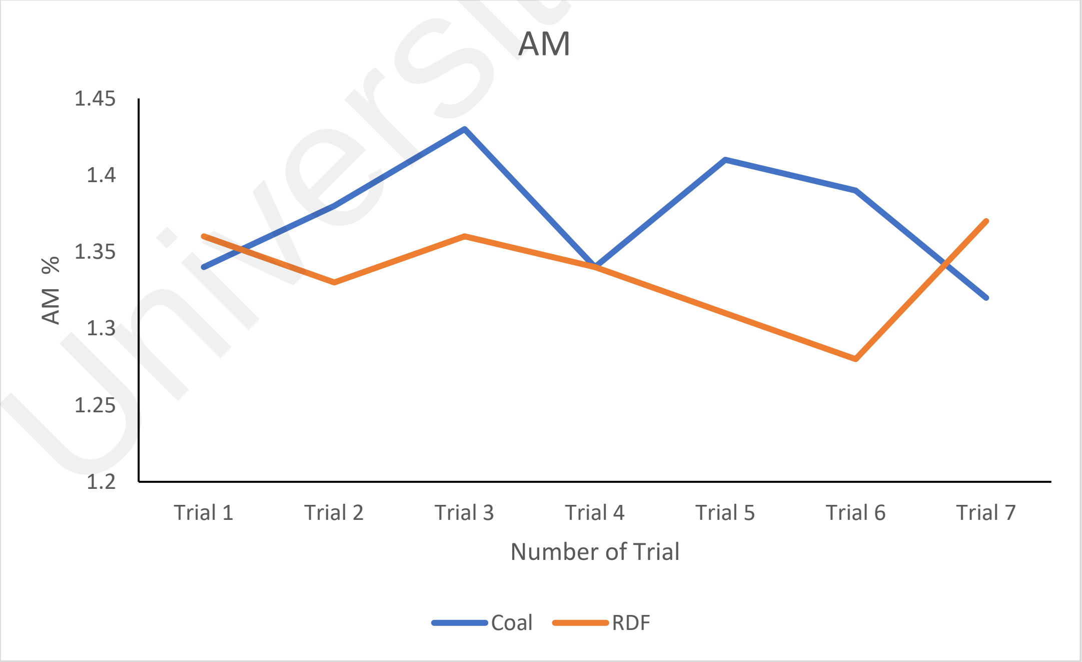


Figure 4.21: AM during co-combustion of coal and 5 MT/hour of RDF

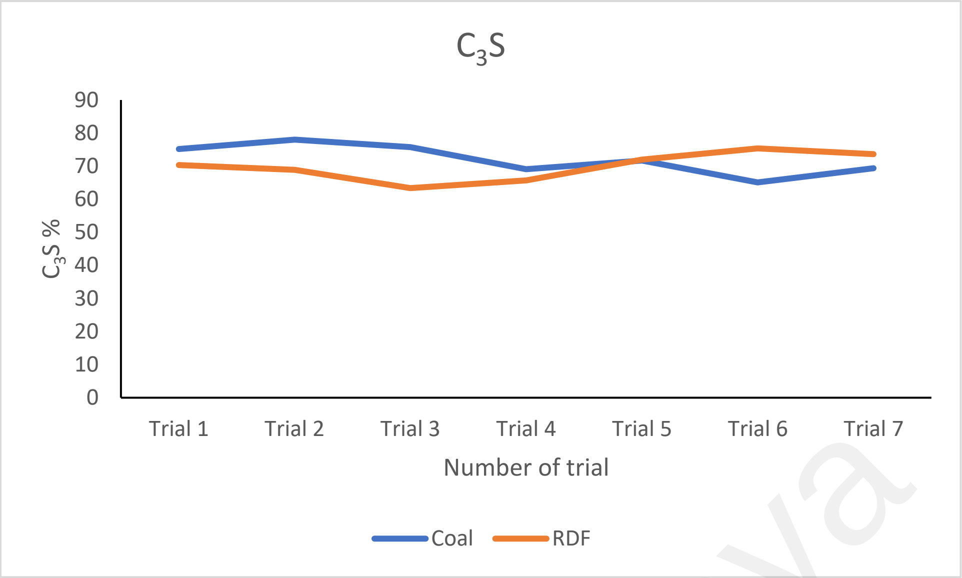


Figure 4.22 :C_3S during co-combustion of coal and 5 MT/hour of RDF

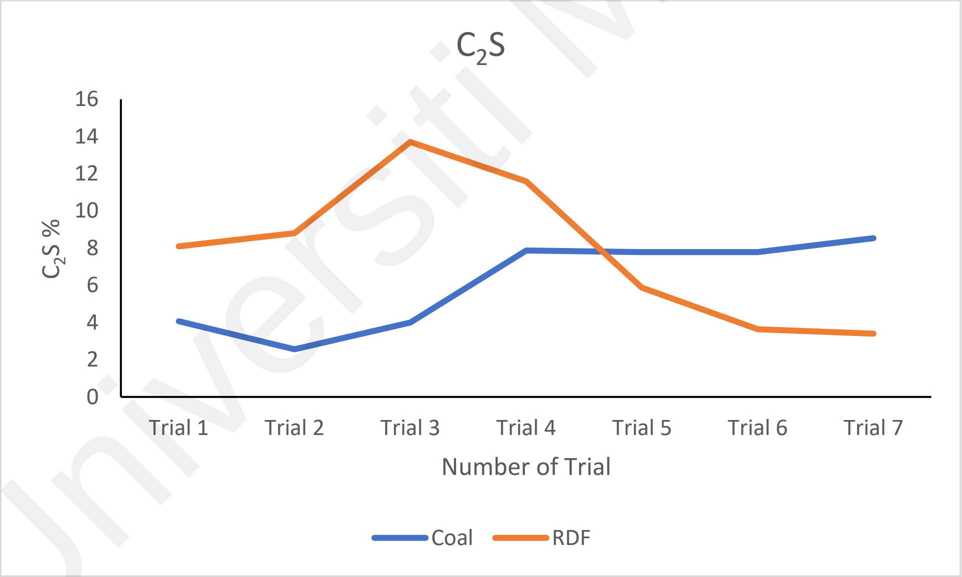


Figure 4.23: C_2S during co-combustion of coal and 5 MT/hour of RDF

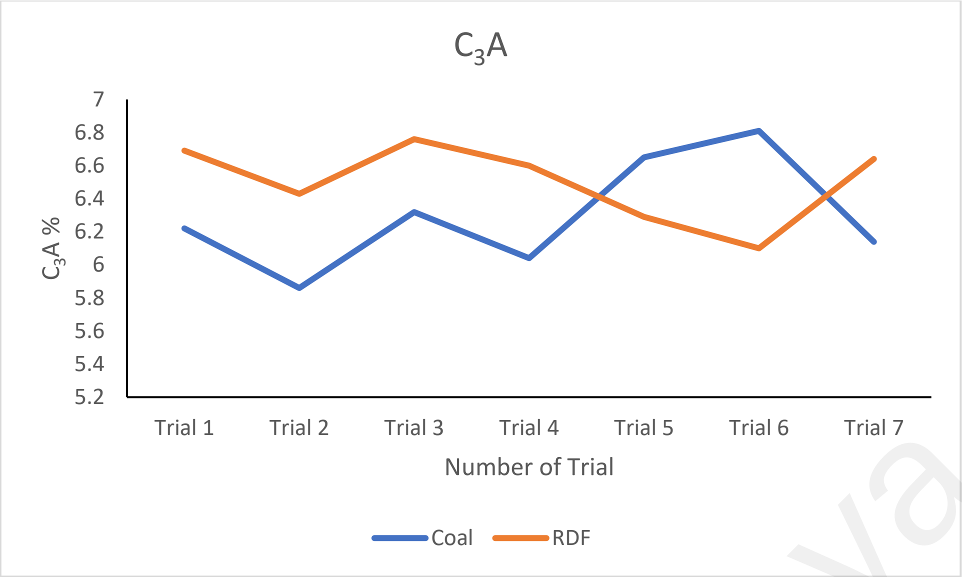


Figure 4.24: C_3A during co-combustion of coal and 5 MT/hour of RDF

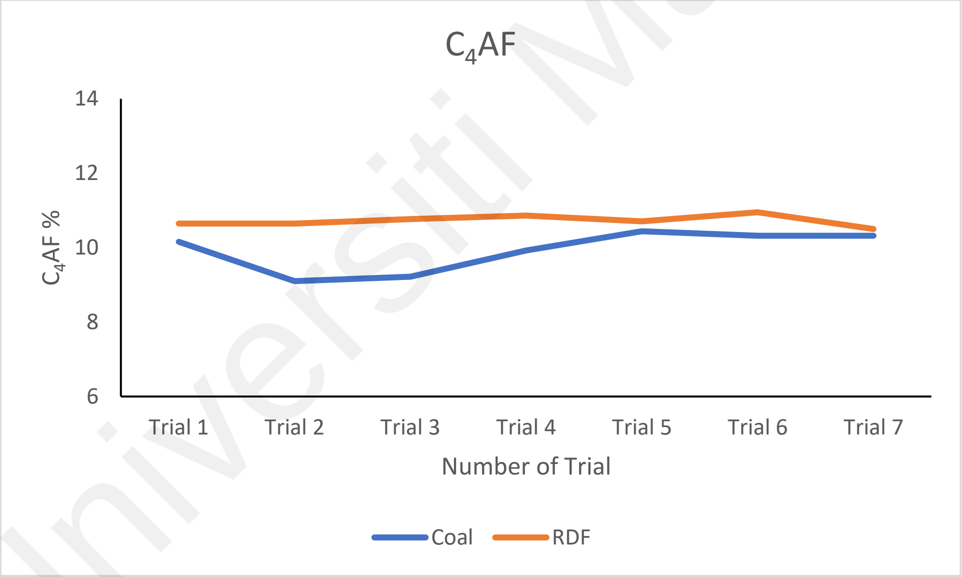


Figure 4.25: C_4AF during co-combustion of coal and 5 MT/hour of RDF

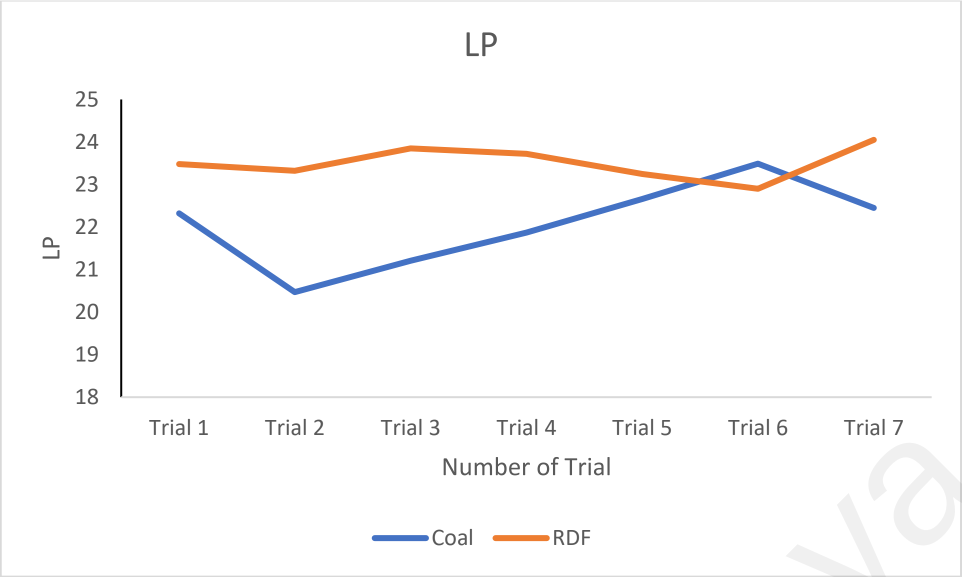


Figure 4.26: LP during co-combustion of coal and 5 MT/hour of RDF

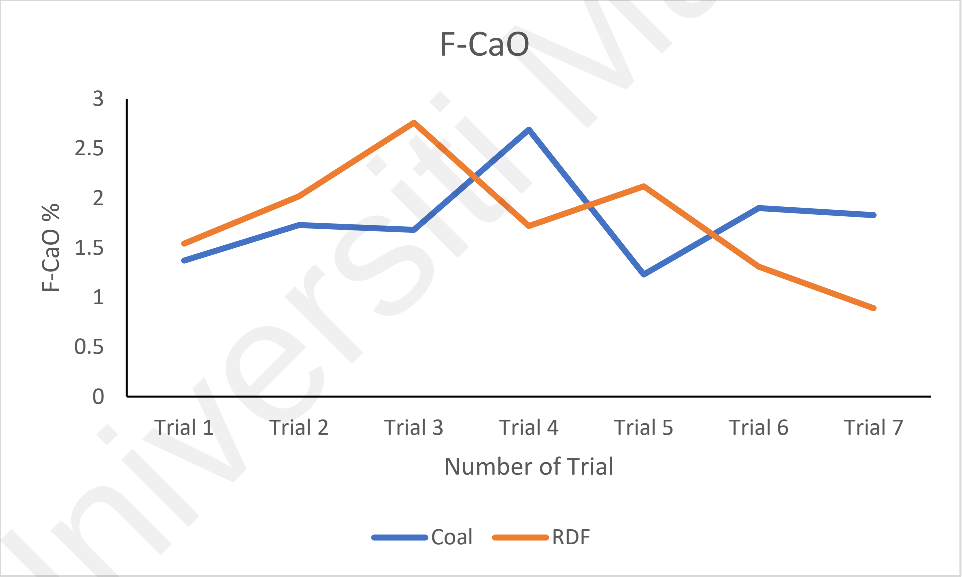


Figure 4.27: F-CaO during co-combustion of coal and 5 MT/hour of RDF

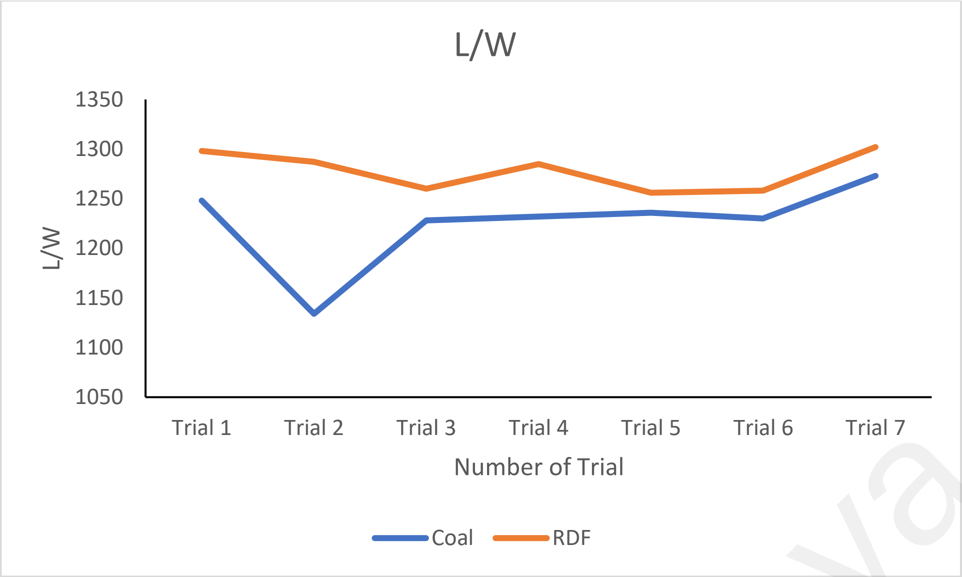


Figure 4.28: L/W during co-combustion of coal and 5 MT/hour of RDF

Table 4.24: Clinker quality information

Parameters	Experimental Result	
	100% coal	**RDF + Coal**
Loss on ignition	0.33	0.25
Silica	21.21	21.33
Alumina	4.48	4.76
Ferric Oxide	3.34	3.50
Calcium Oxide	67.9	67.76
Magnesium Oxide	0.96	0.91
Sulfur Trioxide	1.12	0.89
Potassium Oxide	0.51	0.54
Free Lime	1.34	1.57
Lime saturation factor	101.71	100.21
Silica modulus	2.71	2.58

4.9 Green House Gases Emission Assessment

4.9.1 CO_2-eq Emission Factors

The emission factors are represented as carbon dioxide equivalent (CO_2-eq) by multiplying CO_2, N_2O, and CH_4 emissions with their respective Global Warming Potential (GWP) coefficient based on the Intergovernmental Panel on Climate Change (IPCC) 100-years GWP coefficients. GWP coefficient from IPCC Fifth Assessment Report, 2014, which is 1, 285, and 28 for CO_2, N_2O, and CH_4, respectively, were used in this study (Pachauri et al., 2014). Table 4.25 shows the emission factors used in this study.

Table 4.25: CO_2-eq emission factors

Sources of CO_2-eq emission	**CO_2-eq Emission Factor**	**Reference**
Electricity	0.585 MT CO_2-eq. MWh^{-1}	Ministry of Science, Energy, Technology, Environment and Climate Change (2017). CDM Electricity Baseline for Malaysia 2019
Water	0.344 kg CO_2-eq. m^{-3}	Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. 2006
Diesel (Lorry)	0.0027 MT CO_2-eq. L^{-1}	
Diesel (Lorry)	0.880 kg CO_2-eq. km^{-1}	IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 2: Energy, Chap. 3, Pg. 3.16, 3.21. 2006
Petrol (Forklift)	0.0023 MT CO_2-eq. L^{-1}	
Natural Gas (Drying)	0.056 MT CO_2-eq. $mmBtu^{-1}$	
Waste incinerated	1.679 MT CO_2-eq. $MT_{\text{waste incinerated}}^{-1}$	IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 2: Incineration and Open Burning of Waste, Chap. 5, Pg. 5.7, 5.22.

An inventory of CO_2-eq emission by the source was calculated by applying the CO_2-eq emission factors to relevant activity data to quantify the carbon footprint of RDF. The calculation adopted methodological approach by 1996 Intergovernmental Panel on Climate Change Guidelines, where the basic equation is:

$$Emission = AD \times EF \tag{4.2}$$

where:

$AD = Activiti\ Data$

$EF = Emission\ Factor$

4.9.1.1 CO_2-eq Emission from Raw Materials Supply

The raw materials used for the manufacturing of RDF are industrial hazardous and non-hazardous wastes obtained from other industrial plants. Hence, the CO_2-eq emission generated due to raw materials extraction is not considered in this study.

4.9.1.2 CO_2-eq Emission from Transportation

The CO_2-eq emission from transportation was calculated using (Eq. 4.3)

$$E_T = E_t(RMG\ to\ SFM) + E_t(SFM\ to\ SFC) + E_t(SFM\ to\ WDF) \tag{4.3}$$

where components of the formula in detail:

$$E_t(RMG\ to\ SFM) = total\ distance\ (km.year^{-1}) \times ef(L.km^{-1}) \times EF_{\ diesel}\ (MT\ CO_{2-eq}\ .\ L^{-1})$$

$$E_t(SFM\ to\ SFC) = total\ distance\ (km.year^{-1}) \times EF_{\ diesel}\ (kg\ CO_{2-eq}\ .\ km^{-1})\ /\ 1000$$

$$E_t(SFM\ to\ WDF) = total\ distance\ (km.year^{-1}) \times\ EF_{\ diesel}\ (kg\ CO_{2-eq}\ .\ km^{-1})/\ 1000$$

$$E_T =\ total\ emission\ from\ transport\ (MT\ CO_{2-eq}\ .\ year^{-1})$$

For the calculation of CO_2-eq emission from company-owned transport (E_t), data were collected on-site, where the respective distance was measured, and fuel efficiency (ef) was monitored to measure the total fuel consumed. Thus, the CO_2-eq emission factor used is in the unit of (MT CO_2-eq. L^{-1}_{diesel}). However, for non-owned transport used for the disposal of wastes generated from the RDF manufacturing plant and delivery of RDF to the consumer (cement plant), data were collected by measuring the total distance and the total number of trips. Thus, the CO_2-eq emission factor used is in the unit of (kg CO_2-eq. $km^{-1}_{travelled}$). CO_2-eq emission from the manufacture of vehicles is not considered in this study.

4.9.1.3 CO_2-eq emission from the Manufacturing of RDF

For the calculation of CO_2-eq emission from the manufacturing of RDF (E_P), data were collected on-site, where the respective quantities were measured and extracted from respective operating documents. CO_2-eq emission from the manufacture of machinery and equipment are not considered in this study, as well as CO_2-eq emission from the treatment of domestic wastewater used by workers in the production plant and CO_2-eq emission from the treatment of domestic wastes generated from administrative activities. The calculation is based Eq. 4.4.

$$E_M =\ E_{electricity\ consumption} +\ E_{water\ consumption} +\ E_{diesel\ consumption} + E_{petrol\ consumption} +\ E_{NG\ consumption} \tag{4.4}$$

where components of the formula in detail:

$$E_{electricity\ consumption} = electricity\ (kWh\ .year^{-1})\ \times\ EF_{electricity}\ (MT\ CO_{2-eq}\ .\ MWh^{-1})/1000$$

$$E_{water\ consumption} = water\ (m^{3}.year^{-1})\ \times\ EF_{water}\ (kg\ CO_{2-eq}\ .\ m^{-3})$$

$$E_{diesel\ consumption} = diesel\ (L\ .year^{-1})\ \times\ EF_{diesel}\ (MT\ CO_{2-eq}\ .\ L^{-1})$$

$$E_{petrol\ consumption} = petrol\ (L\ .year^{-1})\ \times\ EF_{petrol}\ (MT\ CO_{2-eq}\ .\ L^{-1})$$

$$E_{NG\ consumption} = NG\ (mmBtu\ .year^{-1})\ \times\ EF_{NG}\ (MT\ CO_{2-eq}\ .\ mmBtu^{-1})$$

$$E_{M} = total\ emission\ from\ manufacturing\ (MT\ CO_{2-eq}\ .\ year^{-1})$$

4.9.1.4 CO$_2$-eq emission from waste disposal

The calculation is based on the following formula (Eqn. 4.5):

$$E_{WD} = E_{W} \tag{4.5}$$

where the component of the formula is as follows:

$$E_{W} = wastes\ from\ manufacturing\ plant\ (MT\ .\ year^{-1}) \times$$
$$EF_{\ W\ incinerated}\ (MT\ CO_{2-eq}\ .\ MT^{-1})$$

$$E_{WD} = total\ emission\ from\ waste\ disposal\ (MT\ CO_{2-eq}\ .\ year^{-1})$$

For the calculation of CO_2-eq emission from waste disposal (E_{WD}), data were collected on-site, where the respective quantities were measured.

4.9.1.5 CO_2-eq Emission from the Use of RDF

The CO_2-eq emission from a cement manufacturing plant is originated from the decarbonization of the raw materials ($CaCO_3 \rightarrow CaO + CO_2$) and combustion of carbon ($C + O_2 \rightarrow CO_2$) in the fuels used for providing energy for the overall endothermic reactions in the kiln system (Lin, Kiga, Wang, & Nakayama, 2011; Wojtacha-Rychter, Kucharski, & Smolinski, 2021). Hence, the emissions generated from the combustion of RDF in a cement manufacturing plant were predicted via the stoichiometric method. Elemental CHNOS analysis was conducted to determine carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S) content. The results obtained from the analysis are then used to calculate the products of combustion.

The calculation of gas emissions from complete combustion is as follows:

Number of mol of the element before combustion

$$N_i = (W_i)/MW_i \tag{4.6}$$

where:

$N_i = \ no. of\ mol\ of\ element\ i\ (kmol)$

W_i
$= \ weight\ fraction\ of\ element\ i\ (obtained\ from\ elemental\ CHNOS\ analysis\ results)$

$MW_i = \ molecular\ weight\ of\ element\ i\ (kg.kmol^{-1})$

Weight of the product (emissions) from combustion

$$E_j = y_j \left(N_j \times MW_j \times W\right) \tag{4.7}$$

where:

$E_j = \text{ Quantity of emission } j\ (kg)$

$y_j = \text{ mol ratio number of gas } j$

$N_j = \text{ no. of mol of gas } j$

$W = \text{ total weight of } IWBSF$

$MW_j = \text{ molecular weight of gas } j\ (kg.kmol^{-1})$

Emissions generated from the complete combustion of RDF in cement manufacturing plants are CO_2, SO_2, and NO_2. However, SO_2 and NO_2 are not included as GHG in IPCC, and hence for the RDF utilization stage, this study only considered emission of CO_2, E_{use}. In addition, this study also included N_2O emission released from the combustion of RDF. CH_4 was not included as the emissions are usually very small and insignificant (Guendehou, Koch, Hockstad, Pipatti, & Yamada, 2006).

4.9.1.6 CO_2-eq Emission from the End Life of RDF

The ash residues generated from the combustion of RDF are used as the raw materials for cement clinker manufacturing (Lam & McKay, 2010). Hence, E_{EL} is concluded to be zero.

4.9.1.7 CO_2-eq Emission from the Full Life Cycle of RDF

Therefore, the total CO_2-eq emission of the RDF life cycle is calculated based on the following formula (Eqn. 4.8)

$$E_{RDF} = E_M + E_T + E_{WD} + E_{utilization} + E_{EL} \tag{4.8}$$

where components of the formula in detail

E_{RDF}	$total\ emissions\ of\ RDF\ \ life\ cycle$
E_M	$total\ emissions\ from\ manufacturing$
E_T	$total\ emissions\ from\ transport$
E_{WD}	$total\ emissions\ from\ waste\ disposal$
$E_{utilization}$	$total\ emissions\ from\ utilization$
E_{EL}	$total\ emissions\ from\ end\ of\ life$

The result shows that the total CO_2-eq emission generated from the cradle-to-grave life cycle of RDF is approximately 28,637 MT. Year $^{-1}$, which is equal to 0.172 kg CO_2e. MJ$^-$1energy generated. In cThe result is summarized in Table 4.26. Figure 4.31 illustrates the details of materials, energy, and CO_2-eq emission flows obtained in this study.

Table 4.26: Summary of the carbon footprint of RDF

CO_2-eq emission source (life cycle stage)	**Emission symbol**	**CO_2-eq (MT. year $^{-1}$)**
Transport	E_T	473.9
Manufacturing	E_M	730.9
Waste disposal	E_{WD}	431.4
Utilization	$E_{utilization}$	27,000.7
End of life	E_{EL}	0
Total	E_{IWBSF}	28,636.9

The sources of CO_2-eq emission based on the life cycle stages and their emission percentages are illustrated in Figure 4.30 and Figure 4.31. It shows that the utilization of RDF at a cement manufacturing plant is the key contributor to RDF's carbon footprint, contributing to 94.3% of the total percentage, with a quantitative value of 28,637 MT CO_2-eq per year. Therefore, the utilization stage can be considered as the environmental hotspot for this study. Furthermore, the second-highest contributor is the RDF manufacturing stage, with a percentage of 2.6. This stage can also be focused on improvement potentials.

4.9.2 Emission Analysis

Table 4.27 summarizes the types and quantities of utilities consumed throughout a year's production of RDF, including water, electricity, natural gas, and fuel. RDF production generates a total of 257.3 MT of waste every year, as shown in Table 4.27b. On the other hand, the total distance travelled annually to transport raw material to the IWSF manufacturer is 419, 805.80 kilometers, followed by RDF distribution to the cement plant and waste disposal (Table 4.27c). The total RDF production rate of 12330 MT was used to calculate the carbon footprint.

The amount of CO_2, H_2O, NO_2, and SO_2 was calculated using the stoichiometric method, and the CHNOS value was acquired using the elemental analyzer. For the RDF utilization stage ($E_{Utilization}$), only the emission of CO_2 is considered as per IPCC, 2014 guidelines. IPCC 2014 was established by the International Panel on Climate Change and incorporates climate change characterization parameters for the direct global warming potential of emissions to air, with a computation timescale of 100 years (IPCC, 2014). This technique excludes indirect effects such as indirect nitrogen monoxide generation, carbon dioxide formation from carbon monoxide emissions, radiative forcing due to NOx emissions, water, and sulphate. As a result, since SO_2 and NO_2 emissions are not recognized as GHGs under the IPCC guidelines, they are not included in this study for CO_2-eq estimation (IPCC, 2014). Additionally, the flue gas emission from the production of IWSF is summarized in Supplementary Table 4.28.

Table 4.27: Type of utility (a), waste generated. (b) and logistic (c) involved in the production of RDF

a)

Types of Utility	**Total Quantity/Year**
Water	1506.00 m^3
Electricity	392, 915.00 kWh
Natural Gas	7615.00 mmBtu
Diesel (Forklift)	25, 231.74 L
Petrol (Forklift)	25, 59.36 L

b)

Waste Generated	**Total Quantity/Year**
SW 409 (Raw materials containers)	254.78 MT
SW 501 (Residue from scrubber)	2.52 MT
Total	257.3 MT

c)

Logistic	**Distance (one way)**	**Total trip per year**	**Total Distance/Year**
Raw material supply			
Raw material to manufacturer			419, 805.80 KM
Waste Disposal			
Manufacturer to licensed contractors	495.50	47	28, 668.0 KM
RDF distribution			
Manufacturer to customer	100	412	82, 400.00 KM

Table 4.28: Flue gas emission from the production of RDF

Flue gas	CO_2	H_2O	NO_2	SO_2
Product Emission (MT/Year)	26,673. 92	66,582. 05	12,153.86	15, 042.61

On the other hand, emission evaluations in the cement plant show that complete combustion of IWSF releases 326.7 MT/year of N_2O when RDF is substituted with Indonesian bituminous coal at a rate of 5 ton/hr (10 %). N_2O emitted during the combustion of RDF ($E_{Utilization}$) in the cement kiln is included in the carbon footprint calculation as it is considered as a greenhouse gas CO_2 and methane. The methane is be assumed not emitted under oxidative combustion of RDF (J Penman et al., 2000). In case traces of methane may accumulate in the waste bunker, the underpressure in the waste bunker causes it to be transferred to the combustion chamber as primary air to be converted along with the bunker air (Guendehou et al., 2006).

4.9.3 Life Cycle Assessment of RDF

Table 4.30 summarizes the total carbon footprint analysis based on the current scenario, which includes the contribution of each life cycle stage of RDF. For the life cycle assessment, RDF is composed of 11763.8 MT/year of hazardous waste, 3064.7 MT/year of non-hazardous waste have been used. The optimized composition of RDF was selected based on CV, availability of the waste and disposal charges. Waste disposal fees are paid to dispose of waste in a landfill and are depending on the weight of the waste. The minimum CV of hazardous waste and biomass of 8.37 MJ/kg and 12.55 MJ/kg, have been used respectively for this analysis.

The cradle to grave (kg CO_2e / MJ energy generated from the combustion of RDF) was calculated by using the equation 4.9:

Total CF emission of per kg product

= ((Total Carbon Emission (kg CO_2e /Year))/ (Total RDF production rate (MT/Year* RDF CV (MJ/kg)*1000) (4.9)

The result shows that the total CO_2-eq emission generated from the cradle-to-grave life cycle of IWSF is approximately 28,637 MT. Year $^{-1}$, which is equal to 0.172 kg CO_2e. MJ^{-1}energy generated. The alternative fuels emit less CO_2 than coal and pet coke due to their lower CO_2 emissions (Sai Kishan et al., 2021; Schneider, 2019).

The sources of CO_2-eq emission based on the RDF life cycle stages and their emission percentages are illustrated in Figure 4.29 and 4.30. The co-firing of RDF with coal in cement kilns is the essential life cycle stage of the RDF process. The analysis shows that the CO_2-eq emission from RDF combustion in cement kilns is significant than RDF production. It's vital to remember that the fuel mix impacts the amount of GHG emissions produced in a cement plant (Chatterjee & Sui, 2019). According to the study conducted by (Reza et al., 2013) alternative fuel as a secondary fuel in cement manufacturing reduces about 3.8 tons of CO_2-eq per ton of RDF utilization as compared to using coal.

As shown in Figure 4.31, the CO_2-eq emission from the RDF production is about 5.8 % of the overall RDF life cycle. It's also important to note that the RDF utilization stage of the cement plant emits more CO_2 than the production stage (Chandrasekhar & Pandey, 2020). Therefore, the utilization stage can be considered as the environmental hotspot in this study. Furthermore, RDF production can be targeted for possible improvements. Figure 4.32 summarized the breakdown of CO_2-eq emission contributors in manufacturing activities. As can be see, waste from the manufacturing and natural gas usage contributes to most of the CO_2 emission in the manufacturing activities.

Table 4.29: Total Carbon Footprint Emission of RDF

Life cycle stage	**Description**	**Component**	**Input Quantity**	**Emission Factor**	**CO_2e emission ($MT CO_2$-eq)**
Raw Materials	Using wastes from other industrial plants	Hazardous waste, Biomass			N/A
Logistic *(ET)*	Raw Materials Suppliers to Manufacturer*Lorry*	Diesel	138329.31 L	0.0027 MT CO_2e / L diesel	***376.21***
Manufacturing of RDF *(EM)*	Process in Manufacturer plant	Water	1506.00 m3	0.3440 kg CO_2e / m^3	***0.52***
	Process in Manufacturer plant	Electricity (Purchased)	392915.00 kWh	0.5850 MT CO_2e / MWh	229.86
	Process in Manufacturer plant	Natural Gas	7615.00 mmBtu	0.0559 MT CO_2e / mmBtu NG	425.96
	Process in Manufacturer plant	Petrol	2559.36 L	0.0023 MT CO_2e / L	5.91
	Process in Manufacturer plant	Diesel	25231.74 L	0.0027 MT CO_2e / L	68.62
					730.87
Waste Disposal-Logistic *(ET)*	Logistic (SW 501 and SW 409 to licensed contractors) Lorry	Mileage	28668.00 KM	0.8803 kg CO_2e / KM	***25.24***

Table 4.29 (continued)

Life cycle stage	**Description**	**Component**	**Input Quantity**	**Emission Factor**	**CO_2e emission (MT CO_2-eq)**
Waste Disposal- Incineration *(E_{WD})*	Waste incinerated	SW 409	254.78 MT	1.6765 MT CO_2e / MT	427.14
	Waste incinerated	SW 501	2.52 MT	1.6765 MT CO_2e / MT	4.22
					431.36
Logistic- Distribution of RDF *(ET)*	RDF to the cement kiln	Mileage	82400.00	0.8803 kg CO_2e / KM	***72.53***
RDF usage in a Cement kiln ($E_{\text{utilization}\textit{tion}}$)	Combustion of RDF in cement kiln	CO_2 emission			26,673.92
		N_2O emission	12330.01	0.0265 MT CO_2e /MT	326.75
					27,000.67
End Life *(E_{EL})*	Waste Residue	Ash			*0.00*
Total carbon emission (MT CO_2e / year) = 28, 636.9 MT CO_2-eq/year					

4.10 CO_2 Emission Reduction Initiatives

The analysis indicates that the waste disposal from RDF manufacturing accounted for 37% of total CO_2-eq emissions, followed by natural gas and electricity use in the manufacturing plant, which accounted for 36 % and 20 % of total CO_2-eq emissions, respectively. Two improvement approaches are identified and implemented to reduce the CO_2-eq emissions produced by electricity during the manufacturing operations of RDF. The initiatives are evaluated in terms of environmental and economic returns.

The sources of electricity consumption in RDF manufacturing are presented in Table 4.30. It was observed that the rotary dryer and a thermal bio fusion machine consumed a significant amount of electricity. Therefore, solar panel was installed in the factory, which provided 97,387.21 kWh of electricity per year. According to the analysis, replacing solar resulted in a 24.8 % reduction in electricity usage, saving 9,766 USD yearly (Table 4.31). Secondly, energy-saving light-emitting diode, LED T5, 28W (4 units), and LED T8, 20W (6 units) bulbs were replaced 70% of the conventional fluorescent bulbs (80 W). By replacing 70% of traditional fluorescent lamps with LED bulbs rated at 28 and 20 watts, an annual electricity bill savings of 45.5 %, or 126 dollars, was achieved. It should be emphasized that the CO_2 emission from solar manufacturing is outside the scope of this study.

Table 4.30: Sources of electricity consumption in RDF manufacturing plant

Source of electricity consumption	Consumption (kWh per month)
2 units of 90 kW thermal bio fusion machine	4,320.0
40 kW of mixer	1,920.0
40 kW of crusher	2,880.0
180 kW of rotary dryer	21,600.0
Others (air conditioning, lighting, etc.)	2,022.9

In summary, replacing solar panel units and LED light bulbs in the RDF manufacturing plant each year could reduce CO_2 equivalent emissions by 60 MT and 0.84 MT, respectively. Besides the improvement initiatives that have been implemented, the manufacturing plant also could adopt other non-investment improvement activities, such as basic housekeeping practices, to minimize CO_2 emissions while also saving the cost of operation.

Table 4.31: Summary of economic and environmental evaluation of electricity improvement initiatives

No.	Improvement initiatives	Estimated annual outcome	
		Cost-saving (USD)	CO_2-eq emission reduction (MT)
1	Installation of solar panel units	9,766.00	60.00
2	Installation of LED energy-saving bulbs for lighting system (LED T5, 28W x 4 units and LED T8, 20W x 6 units)	126.00	0.84

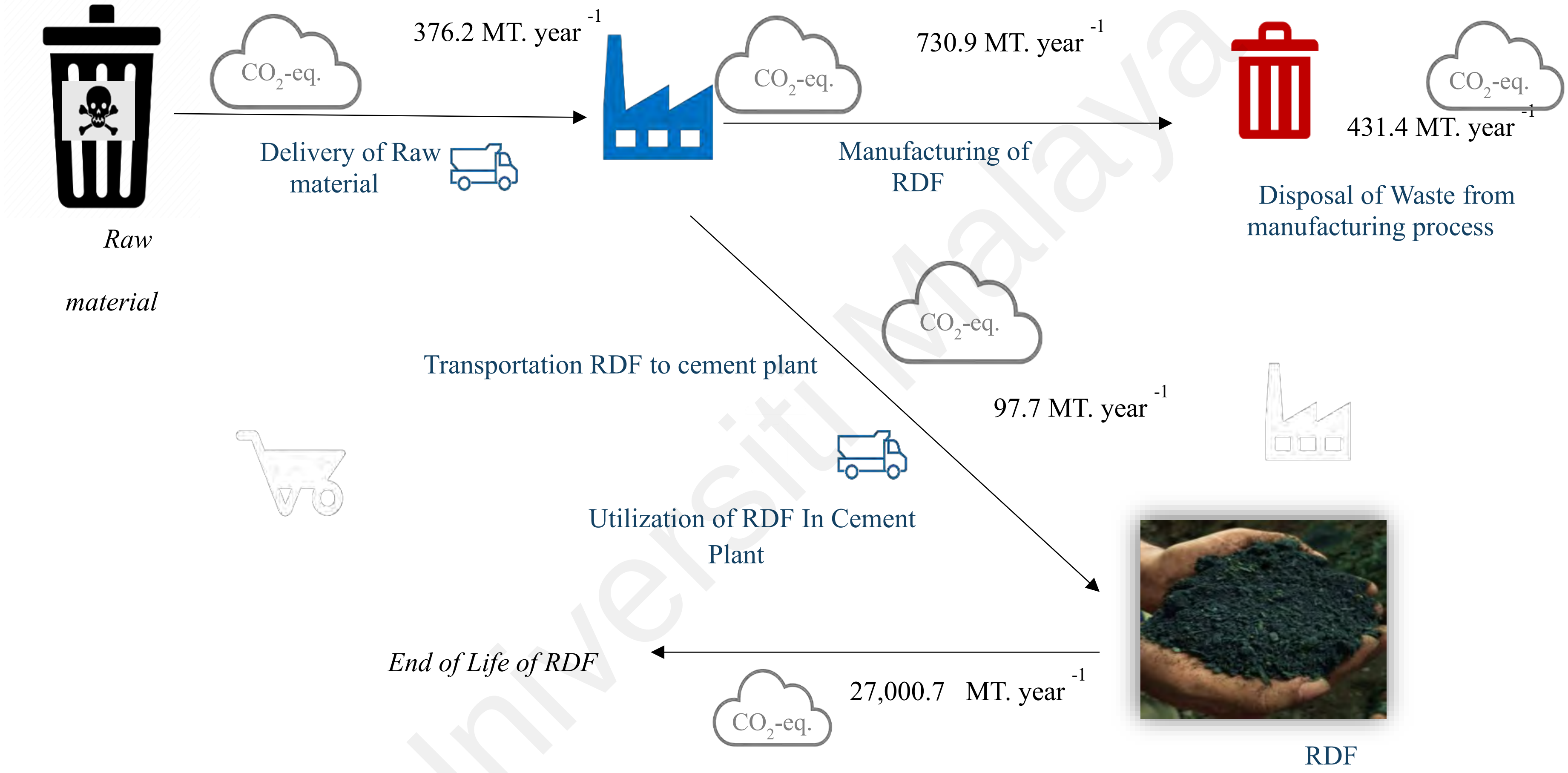


Figure 4.29: Carbon dioxide emission from RDF

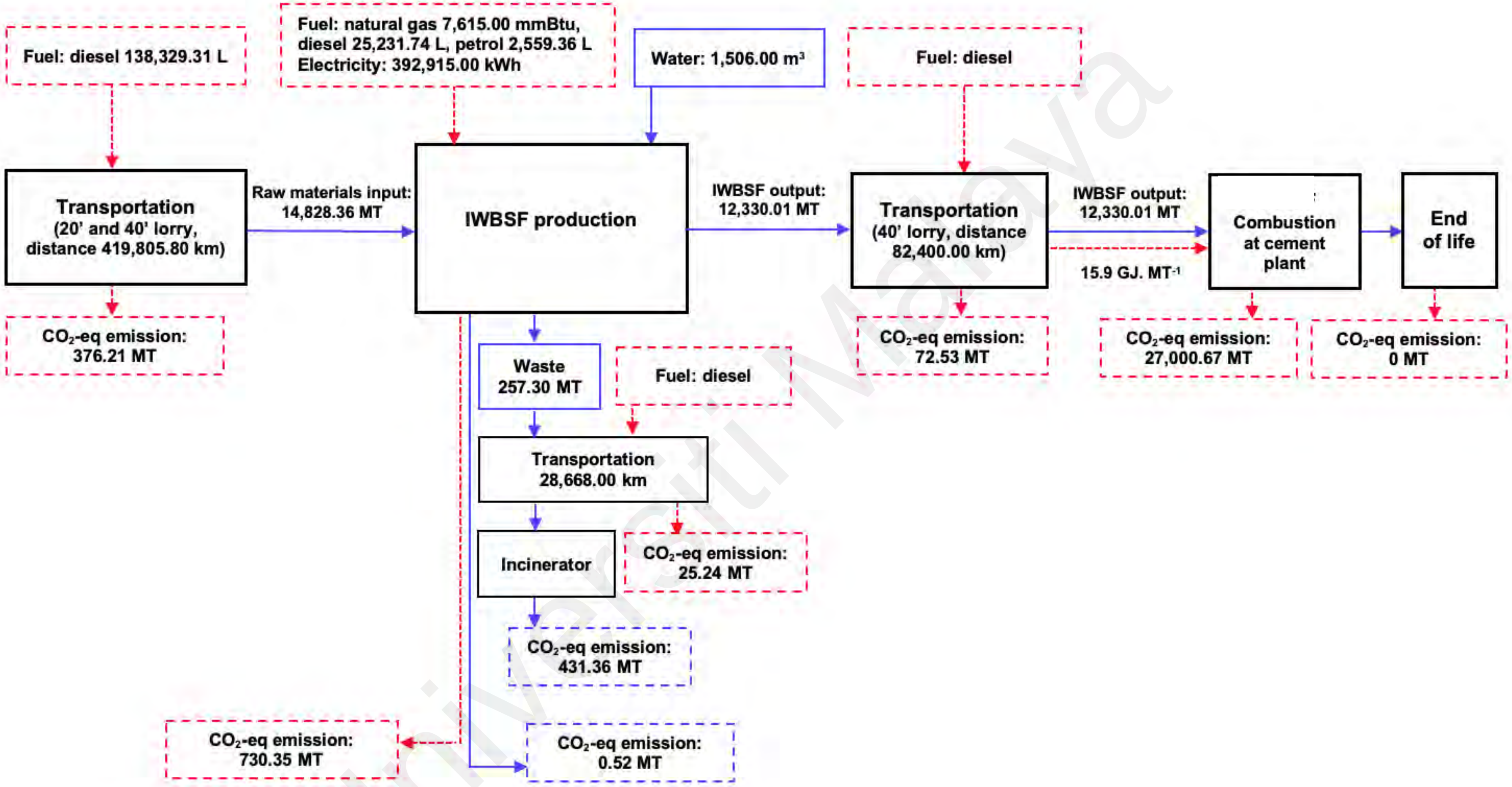


Figure 4.30: Flow analysis of materials, energy, and CO_2-eq emission

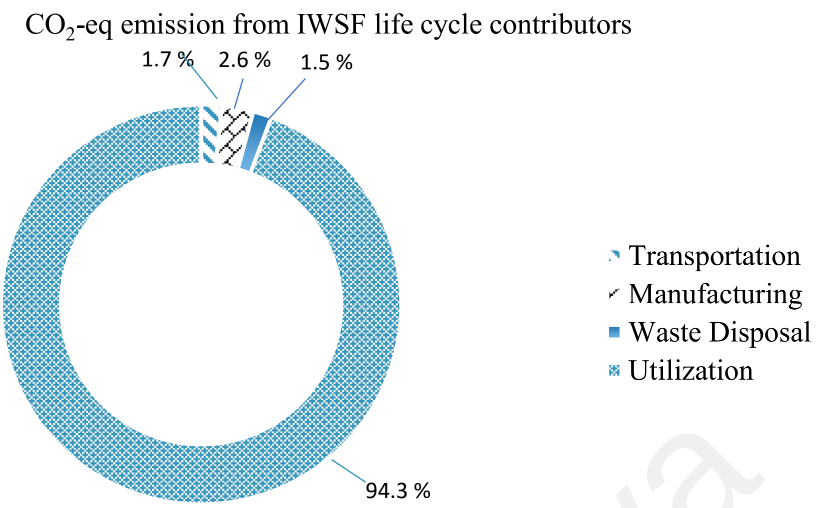


Figure 4.31: Breakdown of CO2-eq emission contributors according to respective life cycle stages

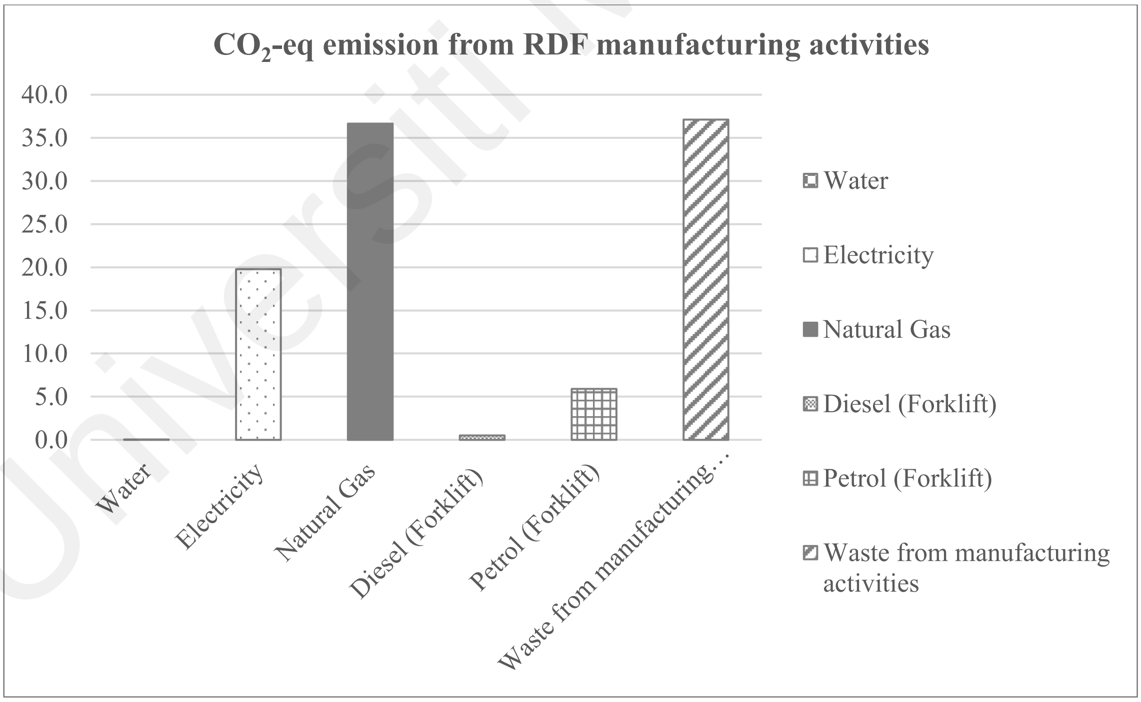


Figure 4. 32: Breakdown of CO2-eq emission contributors in manufacturing activities

4.11 Comparison of CO_2-eq Emission of RDF with the Other Fuel

The CO_2–eq emission of RDF developed in this study has been compared with the other published work. The GWP is measured relative to the mass of CO_2 and evaluated for a 100-year scale. As shown in Table 4.32, the CO_2–eq emission of RDF is significantly lower than that of other alternative fuels derived from municipal solid waste (MSW). Besides, the calculation for GHG emission from using coal established by National Environment Agency , Singapore revealed that the kg CO_2-eq of coal is higher that RDF developed from this work. Additionally, the results of a previously published paper, also observed that solid fuels derived from hazardous waste emit fewer greenhouse gases than other AF.

Table 4.32: Comparison of CO_2-eq of RDF with other fuel

Type of Fuel	kg CO_2-eq (GWP-100 years scale)	Reference
RDF	0.172	This study
Coal	2.03	National Environment Agency , Singapore
RDF -MSW	1.697	(Nutongkaew et al., 2014)
RDF-Palm Kernel Shell	1.423	
Battelle (RDF)	1.250	(Nuss et al., 2013)
MTCI (RDF)	1.019	

4.12 Economic Assessment

The section discusses the savings gained by RDF utilization in the selected cement kilns. The economic assessment will be done for 5 tons/hour of RDF feed together with the coal. The previous study emphasized that the RDF amount of less than 15 % did not affect the cement production process (Hemidat et al., 2019).

i. Total Energy Consumption is 2991.6 kJ /kg.cl

ii. Daily Clinker production quantity is 5000 ton/day

iii. The calorific value of RDF is 4457 kcal/kg

iv. The calorific value of coal is 24,267 kJ/kg (5799.9 kcal/kg)

v. The cost of 1 ton of coal is USD 60 based on the current market price

vi. The production cost of 1 ton of RDF is estimated to be USD 24.24 (Kara, 2012)

vii. Total requirements of energy per day = 2991.6 kJ/kg.cl. X 5000 tons/day X1000
= 14,958,00 kJ/day

viii. Total Coal of required per day =14,958,000 kJ/day / 24,267 kJ/kg = 616.4 ton/day

ix. Feed rate of coal = 616.4 tons/day / 24 hour= 25.7 ton/hour

x. If feeding rate of RDF 5 tons/hr = 5 tons/hr x 18,652 kJ/kg x 24 h per day
= 2,238,240 kJ/day

xi. If feeding rate of RDF 8 tons/hr = 8 tons/hr x 18,652 kJ/kg x 24 h per day
= 3,581,184 kJ/day

xii. Feed rate of coal (5 tons/hour RDF) = (14,958,000 - 2,238,240) kJ / 24 h per day / 24,267 kJ/kg
= 21.8 ton/hour

xiii. Feed rate of coal (8 tons/hour RDF) = (14,958,000 - 3,581,184) kJ / 24 h per day / 24,267 kJ/kg
= 19.5 ton/hour

xiv. The energy consumption of coal to produce 5000 ton/day is: 5000 tons/day X 1000 X 715 kcal/kg.clinker. = 358 X 10^7 kcal/kg.cl.
= 1.498 x10^{10} kJ.kg.clinker

xv. The coal energy consumption saving, when 15 % RDF (5 tons/hour of RDF) is used in the main fuel: 358 X 10^7 kcal/kg.cl. X 0.15

= 537 X 10^6 kcal/kg.clinker

= 2.246 X 10^9 kJ.kg.clinker

xvi. The RDF amount to be substituted per hour to achieve the required energy of 537 X 10^6 kcal/kg.cl.:

537 X 10^6 kcal/kg.clinker /4457 kcal/kg.clinker./1000/24 h per day = 5 ton

xvii. The coal amount per hour in to achieve the required energy of 3033 x10^6 kcal/kg.cl is: 3033 x10^6 kcal/kg.cl./ 5799.9 / kcal/kg /1000/24 h per day = 21.8 ton/h.

xviii. When 15 % of RDF is used in the primary coal, the annual coal saving is:

3.9 tons/h X 24 h/day X 300 day/year = 28, 080 ton/year

xix. The cost of 1-ton coal to the cement plant is USD 60 on the basis of current market prices; thus, the annual income is:

28, 080 tons/year X 60 USD /ton = 1, 684, 800 USD/year

xx. Since RDF consumption is 5 tons/h, when 15% RDF is used in the main fuel, the annual consumption of RDF becomes: tons/h X 24 h/day X 300 day/year = 36,000 ton/year

xxi. The cost of 1-ton RDF to the cement plant is 24.24 USD based on current market prices; the annual cost is: 36,000 tons/year X 24.24 USD/ton = 872, 640 USD/year

In this state, the actual financial saving of using RDF:

1, 684, 800 USD/year - 872, 640 USD/year = 812, 160 USD/year

4.13 Environmental Evaluation

The cement industry is one of the main contributors of CO_2 emissions as high temperatures, about 1450°C are needed in the cement kiln to calcinate the raw material for the production of cement and the combustion of fuels (Bakhtyar, Kacemi, & Nawaz, 2017). Cement manufacturing emits carbon dioxide CO_2 both directly and indirectly. Carbon dioxide is a by-product of calcination that is used in the production of clinker. During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln to form clinker (i.e., calcium oxide or CaO) and CO_2. This process is known as calcination or calcining. The process releases carbon dioxide into the atmosphere.

Table 4.33 shows the CO_2 emission by adding RDF as a substitute fuel in the coal. In addition to combustion-related emissions, cement production also is a source of process-related emissions resulting from the release of CO_2 during the calcination of limestone. As shown in Table 4.35, a higher total CO_2 of 5.19 is emitted when coal alone was used as the primary fuel from the incineration (3.1 ton CO_2/ ton of HWs) and fuel combustion (2.10 ton CO_2/ ton of HWs processes. However, when RDF (5 ton/hour) was added to the coal via the alternative feeding line, the amount of carbon dioxide is comparatively lower, 2.94 ton CO_2/ ton of HWs. The results show that although coal releases less CO_2 during combustion, the total CO_2 emissions from coal are two times greater when 15% of RDF is substituted in coal.

Table 4.33: Carbon dioxide emission by RDF and coal

Type of Fuel	**CV (kJ/kg)**	**CO_2 released (ton CO_2/ ton of HWs)**			
		Incineration of hazardous industrial wastes in landfill	**Fuel Production**	**Fuel Combustion**	**Total**
RDF	4457	None	0.48	2.46	2.94
Coal	5800	3.1	None	2.10	5.19

The net saving for the process is calculated based on RDF production cost, coal saving cost, and carbon dioxide emission saving. Table 4.34 provides the net savings in the total operational costs and carbon dioxide emissions by using RDF as a substitute fuel for the coal in the selected cement industry. The calculation is based on 70% of 1 kg of coal is emitted as carbon dioxide. The cost of emissions of 1 ton of CO_2 is USD 15. The calculation based on the total operational costs and carbon dioxide emissions by substituting 15% of RDF in the coal.

i. CO_2 emission savings in coal:

3.9 ton/hour X 0.70 X 24 hour X 300 days = 18,144 ton/year

18,144 ton/year X 15 USD/ton = 272, 160 USD/year

The efficiency loss is 20% X RDF % consumption X 100

= (0.20 X 0.15) X 100 = 3 %

Therefore, based on the abovementioned equations, the net cost saving is:

ii. ((Coal saving + CO_2 emission saving in coal -RDF production cost) X (100 - efficiency loss))/100

((1, 684, 800 USD/year + 272, 160 USD/year - 872, 640 USD/year) X (100 - 3))/100

= 1, 051, 790 USD/year

Table 4.34: Economic model for using RDF in the coal for cement kiln

Parameter	Unit	Condition 1	Condition 2	Condition 3
Rate of RDF	ton/hour	0	5	8
Rate of coal	ton/hour	25.7	21.8	19.5
RDF substitution ratio	%	0	15	24
Coal consumption ratio	%	100	87	76
Coal savings	ton/year	0	28,080	44, 640
Coal savings	USD/year	0	1,684, 800	2,678, 400
CO_2 emission savings in coal	ton/year	0	18,144	31, 248
CO_2 emission savings in coal	USD/year	0	272, 160	468, 720
RDF production cost	USD/year	0	872, 640	1,282,176
Net savings	USD/year	0	1, 008 418	2, 874,035

4.14 Standard Handling Procedure for RDF in the Cement Plant

The standard operating procedure developed in this study for Refused Derived Fuel derived from mixed of hazardous waste and biomass were based on the available analytical, OSHA and industrial hygiene information based on fact finding only. No evaluation of potential additive or synergistic effects were considered in the development of this handling procedure. Individuals receiving the information must exercise their independent judgment in determining its appropriateness for particular purpose or use.

1. Identification of the Substance / Preparation and Company Undertaking

Product name	:	Refused Derived Fuel (RDF)
Primary Components	:	The RDF consists of a combination of selective organic waste, Indigenous biomass & natural binders

2. Composition/Information on ingredients

Physical composition

Items	Weight
Biomass	10 – 30%Fraction
Industrial Waste	70 – 90%

Chemical Composition

Items	Symbol	Typical PPM
Arsenic	As	<500
Barium	Ba	<1000
Cadmium	Cd	<100
Copper	Cu	<2500
Chromium	Cr	<2500
Lead	Pb	<100
Mercury	Hg	<0.01
Nickel	Ni	<1000
Selenium	Se	<0.01
Silver	Ag	<0.01
Zinc	Zn	<1000

3. Hazards Identification

General Physical Form: Solid

Immediate health, physical, and environmental hazards:

1. Possible hazard caused by dust particulates.
2. There is possibility of ignition may be caused by a flammable mixture coming in contact with RDF at a Flash Point of minimum 300 C enough to cause MAF to auto-ignite.
3. On contact with water- If a spill occurs, there is a surface water contamination hazard.

Potential Health Effects

Eye

Acute	:	May cause mechanical irritation. Irritating, but will not permanently injure eye tissue.
Chronic	:	Low hazard for usual industrial handling

Skin

Acute	:	May cause mechanical irritation and skin drying.
Chronic	:	May cause dermatitis

Inhalation

Acute	:	Dust may be irritating to respiratory tract. Provide appropriate exhaust ventilation at machinery and at places where dust can be generated.

Chronic : May induce vomiting and nausea.

Ingestion

Acute : Dust may be irritating to respiratory tract. Provide appropriate exhaust ventilation at machinery and at places where dust can be generated.

Chronic **:** May induce vomiting and nausea.

4. First aid measures

Inhalation : If overcome by dust, remove to ventilated area. Consult a physician.

Eye Contact: : Flush eyes immediately with large amounts of water at least for 15 minutes, keeping the eyelids opened to assure a complete rinsing.

Skin Contact : Remove contaminated clothes. Wash skin thoroughly with soap and water. Wash contaminated clothing as desired

Ingestion : Drink plenty of water. Get physician help.

5. Firefighting measures

Extinguishing Media **:** Use dry chemical, carbon dioxide, or water spray. A fog spray is recommended if water is used. DO NOT USE a solid water stream as it may scatter and spread fire.

Special Protective Equipment for Firefighters **:** Wear suitable protective equipment. In the event of fire, wear self-contained breathing apparatus. Wet MAF produces very slippery walking surfaces.

Specific Hazards : It may not be obvious that MAF is burning unless the material is stirred, and sparks are apparent. MAF that has been on fire should be observed closely for at least 48 hours to ensure no smoldering material is present. Burning produces irritant fumes. This MAF is insoluble and floats on water. This MAF creates a fire hazard because it floats on water.

Hazardous Decomposition and/or Combustion Products : Carbon monoxide, carbon products of combustion.

Risk of Dust Explosion : Do not create a dust cloud by using a brush or compressed air

6. Accidental release measures

Personal Precautions : Caution: Wet RDF produces slippery walking surfaces. Avoid dust Formation. Ensure adequate ventilation. Use personal equipment.

Methods of cleaning : Clean up promptly by vacuum. Use vacuum with high efficiency particulate air (HEPA) filtration is recommended. Do not create a dust cloud by using a brush or compressed air. Pick up and transfer to properly labelled containers.

7. Handling and storage

Stability	:	Material is stable under normal storage and handling situations.
Hazardous Decomposition Products	:	N/A
Hazardous Polymerization:	:	N/A
Storage		Keep in dry, cool and well-ventilated place. Keep away from heat and sources of ignition. Do not store together with volatile chemicals as they may be adsorbed onto MAF. Keep in properly labeled containers.
Handling		Avoid contact with skin and eyes. Do not breathe dust. Provide appropriate exhaust ventilation at machinery and at places where dust can be generated. Do not create a dust cloud by using a brush or compressed air. Fine dust is capable of penetrating electrical equipment and may cause electrical shorts. Take precautionary measures against static discharge. If hot work (welding, torch cutting, etc) is required the immediate work area must be cleared of RDF and dust.

8. Exposure control/ Personal Protection

Engineering Controls	:	Ensure adequate ventilation to maintain exposures below occupational limits. Provide appropriate exhaust ventilation at machinery and at places where dust can be generated.
Administrative Control	:	Training must be conducted before routine and non-routine handling.
Personal Protection		
Respiratory Protection	:	An approved air-purifying respirator (APR) for particulates may be permissible where airborne concentrations are expected to exceed occupational exposure limits. Protection provided by air-purifying respirators is limited. Use a positive-pressure, air supplied respirator if there is any potential for uncontrolled release, exposure levels are not known, or nay circumstances where airpurifying respirators may not provide adequate protection. Use respirators must include a complete respiratory protection program in accordance with national standards and current best practices.
Skin Protection	:	Wear suitable protective clothing. Washing clothing daily. Work clothing should not be allowed out of the workplace.

Hand Protection : Wear protective gloves to prevent soiling of hands. Use protective barrier cream before handling MAF. Wash hands and other exposed skin with mild soap and water.

Eye Protection : Wear eye/face protection. Safety glasses with side-shields. Goggles.

Others : Employ good personal hygiene and work practices such as frequent hand washing with soap and water, regular clothing changes, and minimizing contact

9. Physical and Chemical Properties

Appearance : Black powder/briquette/smaller size with 90 mm [W] x 150 mm [L] diameter solids with variable length

Physical state : Solid

Odour : None to slight

pH : 6.3 – 7.4

Bulk density : 800 kgm^{-3} – 1200 kgm^{-3}

Viscosity : N/A

Volatiles by vol. % : 10-30

Boiling point : N/A

Melting point : N/A

Flash point : Minimum 300 C

Auto Ignition Temp : Not Determined

Calorific Value : 4000kcal/kg to 4200 kcal/kg

Burn Velocity : Not Determined

Dust Explosion Classification : Not Determined

Maximum Absolute Explosion Pressure : Not Determined

Solubility in water : Insoluble

Maximum Rate Pressure Rise : Not determined

Ignition Energy: : Not determined

Decomposition Temperature: : Not determined

10. Stability and Reactivity

Stability : Stable under normal handling

Reactivity : May react exothermically upon contact with strong oxidizers.

Incompatible Materials : Not Determined

Conditions to Avoid : Do not expose to temperatures above 300ºC. Keep away from oxidizing agents to avoid exothermic reactions.

Hazardous Decomposition and/or Combustion Products : Carbon monoxide, carbon dioxide, Oxides of sulphur, organics products of combustion.

Static Discharge Effects; : Take precautionary measures against static discharges. Avoid dust formation. All metal parts of the mixing and processing equipment must be earthed/grounded. Ensure all equipment is electrically earthed/grounded before beginning transfer operations.

11. Toxicology information

Skin : May be abrasive to the skin

Eye : Can cause eye irritation

Ingestion : Irritation of the gastrointestinal tract, nausea, vomiting; may be fatal if ingested in large quantities

12. Ecological information

There is no data available to determine ecological hazards for this product

13. Disposal considerations

Not considered a Hazardous Material or Hazardous Waste. Waste categorized as SW 421 and SW 422 must be disposed by Kualiti Kitar Alam of in an environmentally safe manner and in accordance with federal, state, and local environmental control regulations under Environmental Quality (Scheduled Wastes) Regulations, 2005.

14. Transport information

DOT	:	Not regulated as a hazardous material by DOT
IATA	:	Not regulated as dangerous goods.
IMDG	:	Not regulated as dangerous goods.
TDG	:	Not regulated as dangerous goods.
General	:	The product is not defined under national/ international road, rail, sea and air transport regulations as hazardous material. The product is a non-activated carbon black of mineral origin. Basing on the studies this product is not being considered a hazardous good according to the classification of hazardous goods 4.2, since self-ignition is above 140 °C.

15. Regulatory information

OSHA Status : N/A

However, Occupational Safety and Health (Classification, Packaging and Labelling) Regulations 1997 may apply

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, RDF was developed from a mixture of hazardous industrial waste and biomass. The use of regulatory-compliant renewable fuels is strongly recommended in the cement industry as it is highly energy-intensive. The aim of this study is to develop RDF with high Calorific Value (CV) from mixed hazardous wastes and biomass and the potential application in cement manufacturing was investigated. It should be noted that this is the first-ever study that used hazardous waste to develop alternative fuel, RDF, to be used in a cement plant.

Five types of mixed hazardous industrial wastes (rubber waste, mixed waste, paint sludge, palm oil sludge and wastewater treatment plant sludge) and three biomass types (sawdust, paddy husk and empty fruit bunch) have been used to develop the RDF in this study. The incoming raw material are prudently selected via the limit set as a waste acceptance criterion (WAC) that ranges from calorific values to the presence of heavy metals to be used in the production of RDF. The hazardous wastes and biomass were pre-prepared in an offsite facility and processed to RDF with a uniformed specification. In the raw or untreated state, hazardous waste may have a different CV value. To accommodate this, modifications to the operating conditions, such as adjusting the feed rate of coal or altering the airflow into the cement kilns' burner, must be made. Therefore, this study's main challenge is producing RDF with a consistent CV, volatile matter, fixed carbon and ash by using the mixture of hazardous waste and biomass. In this study, RSM-CCD in the Design-Expert software was selected to optimize the RDF composition to achieve the predetermined CV, volatile matter, fixed carbon, moisture and ash content. The RSM-CCD model proposed 542 experiments. Then, the selected RDF samples have been characterized to meet the alternative fuel guidelines for the cement manufacturing industry. The emissions generated from using RDF in the cement kilns are also studied. The systemic environmental and economic evaluation of RDF developed using hazardous waste and biomass to unravel the potential opportunities of the new concept of renewable fuels and contribute to the cement industry to reduce carbon pollution.

Based on the RSM-CCD models obtained and input criteria, the RDF from the hazardous industrial waste and biomass are formulated. The optimum combination is selected based on the CV, VM, FC, and ash content. The result showed that the optimum ratio of hazardous wastes to biomass with the maximum CV of RDF was 1:0.01. The optimized composition of RDF was selected based on CV, availability of the waste and disposal fee. The selected RDF has a CV of approximately 18,652kJ/kg, comparable to with the bituminous coal sample, 24,267kJ/kg and its volatile matter, fixed carbon and ash content of 32 %, 40% and 28%, respectively. The calorific value of the RDF developed in this study is considerably higher than previously developed form municipal solid waste. Besides, the RDF specification are in compliance with the stipulate criteria outlined in Fuel acceptance criteria, guidelines Guidelines for Application of Special Management of Scheduled Wastes and Guidelines for Environmentally Sound Co-Processing of Scheduled Wastes in Cement Factory in Malaysia.

This study also confirmed the usability of generated RDF as an alternative for bituminous coal in the selected cement manufacturing industry. The potential environmental benefits and effects of substituting the RDF for the coal in the selected cement plants were also evaluated. Actual trial runs were conducted for three months in the chosen cement plant, where 5 tons/hour (13 %) and 8 tons/hour (23 %) of RDF is fed into the rotary kiln substituting the coal, via a separate feeding line, based on two different conditions. The study is revealed that substituting 5 ton/hour of RDF in the coal only emits about 301 mg/m^3 of NOx, which is within the regulatory limits in Malaysia. Besides, the emission of heavy metals, including Zinc, Arsenic, Lead, Copper, Antimony, and Chromium, was also within the regulatory limits, Environmental Quality (Clear air) regulation 1978.

RDF in cement manufacturing kilns is economically and environmentally attractive, as the combustion of RDF allows for a reduction of about 2.25 kg of CO_2 per kg compared to coal. In terms of the efficiency of clinker and stack gas emission values, the substitution of 13 % of RDF to the coal at a feeding rate of 5 ton per hour in cement production did not cause any processing and quality issues in the existing cement production process. Besides, the savings gained by RDF utilization in the selected cement kilns also evaluated. The economic assessment was done for 5 tons/hour of RDF feed together with the coal. The result revealed that substituting 13 % of RDF with the coal in 5000 ton/day cement plant may reduce 112.8 USD/hour in operating cost. Additionally, 140 USD/hour of net saving could be achieved by saving 2.52 ton/hour of CO_2 emitted from the cement production.

Thus, it can be concluded that development of RDF from hazardous waste is an accepted and suitable product to be used as alternative fuel to reduce the dependence of coal in the production of clinker in the cement manufacturing plant. Overall, the results concluded that RDF is a very promising resource recovery and waste treatment option for hazardous waste management.

5.2 Recommendation for Future Work

The following aspects could be explored further to obtain more information and insight into RDF development using hazardous waste.

1. Conduct investigation into thermo-chemical characteristic that includes kinetic and mechanism of co-firing of coal and RDF.
2. Conduct detailed study on producing RDF from hazardous waste for house-hold applications which may require alternative and processes and quality control.
3. To expand the hazardous waste codes used for the RDF development which requires in depth study of their characteristics.
4. Study the potential application of the RDF develop this study in power plant and other energy plant.

5.3 Knowledge Contribution

Two high-impact publications have been developed from this work. The details are given in appendix A. The following is the knowledge contribution from this work.

1. A proven process flow for transforming hazardous waste to RDF.
2. Develop the waste acceptance criteria for RDF from hazardous waste.
3. Develop analytical method for characterizing RDF.
4. Develop SOP for handling RDF from hazardous waste.

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