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Department of Waste and Resource Management

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VIABILITY OF REFUSE-DERIVED FUEL (RDF) FROM MUNICIPAL SOLID WASTE (MSW) AS A SUSTAINABLE ALTERNATIVE FUEL FOR THE CEMENT PLANT IN CITEUREUP, WEST JAVA, INDONESIA.

DISSERTATION

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The Academic Board of Rostock University

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DECLARATION OF INDEPENDENCY

I hereby declare by my own signature that I have written this dissertation independently and not to have used any sources or aids other than those specified. Those from the sources directly thoughts adopted or indirectly adopted are identified as such. The dissertation in this form has not yet been submitted to any other testing authority.

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SUMMARY

Indocement, a cement producer in Indonesia, aims to replace 50% of its coal with alternative fuels by 2030. This study explores the use of Refuse Derived Fuel (RDF) from Municipal Solid Waste (MSW) as fuel in the cement plant to enhance waste management and sustainability in the sector. Analysis of 1,265 Mg of MSW from Jakarta, Bogor, Depok, and Bekasi revealed that the MSW was unsuitable for RDF production due to high moisture (55%) and low LHV (5.4 MJ/kg). However, with 80-90% combustibility, RDF shows significant potential.

The study evaluated four RDF production pilot projects. Strategy 1 used a 16-day bio-drying process, reducing moisture to 30%. Strategy 2 employed both solar and bio-drying, achieving similar RDF quality to Strategy 1 in 13 days. Strategy 3, using only mechanical treatment, produced RDF with high moisture (47-61%). Strategy 4 combined mechanical treatment with a belt dryer, achieving 34% moisture. These results indicate that drying processes are crucial for enhancing RDF quality.

The RDF from the pilot project was utilised by the cement plant. Strategy 1 achieved the highest net energy production at 7259 GJ and the greatest CO_2 reduction of 334 Mg. Strategy 2 followed closely with 7256 GJ of net energy and a CO_2 reduction of 331 Mg. Strategy 3 produced 4969 GJ of net energy and reduced CO_2 by 217 Mg, while Strategy 4 generated the least net energy at 4457 GJ and had a CO_2 reduction of 159 Mg. Overall, strategies 1 and 2 were the most effective in both energy production and CO_2 reduction.

Four modelling scenarios, each processing 500 Mg/day of MSW, were evaluated. The RDFP-3 model, which involves drying RDF and low-grade RDF in the cement plant, was found to be the most cost-effective with the shortest payback period of 6 years, requiring 186.8 million euros and additional land. To achieve a 50% substitution rate, processing 6,500 Mg/day of MSW would yield 3,100 Mg/day of RDF, potentially reducing coal consumption by 608,000 Mg/year and CO_2 emissions by 586,000 Mg/year. Compliance with Indonesian standards is feasible, but adhering to stricter German regulations would require improved Cl bypass systems and enhanced scrubbing and filtering technologies.

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LIST OF ABBREVIATIONS

AF: Alternative Fuel

APAC: Asia Pacific

Ar.: As Received

ASI: *Asosiasi Semen Indonesia* (Indonesian Cement Association)

ASTM: American Society for Testing and Materials

BaP: Benzo[a]pyrene

BI: Bank of Indonesia

BMUV: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Germany)

BPKRI: *Badan Pengelola Keuangan dan Risiko Infrastruktur* (Infrastructure Financial and Risk Management Agency)

BPS: *Badan Pusat Statistik* (Statistics Bureau of Indonesia)

BSNRI: *Badan Standardisasi Nasional Republik Indonesial* (National Standardization Agency of Republic of Indonesia)

C: Carbon

C_2S: Dicalcium Silicate

C_3A: Tricalcium Aluminate

C_3S: Tricalcium Silicate

C_4AF: Tetracalcium Aluminoferrite

$CaCO_3$: Calcium Carbonate

CaO: Calcium Oxide

Capex: Capital Expenditure

Cd: Cadmium

Cembureau: European Cement Association

CEMS: Continuous Emission Monitoring System

CEN: European Committee for Standardization

CGA: Cylinder Gas Audit

Cl: Chlorine

CNR: National Research Council

CO: Carbon Monoxide

CO_2: Carbon Dioxide

Cr: Chromium

Cu: Copper

Db.: Dry basis

DDP: Delivered Duty Paid

DKI Jakarta: *Daerah Khusus Ibukota Jakarta* (Special Capital Region of Jakarta)

DLH: *Dinas Lingkungan Hidup* (Environmental Agency)

DMO: Domestic Market Obligation

EEA: European Environment Agency

EIA: Environmental Impact Assessment

EP: Electrostatic Precipitators

EPR: Extended Producer Responsibility

ESDM: *Energi dan Sumber Daya Mineral* (Ministry of Energy and Mineral Resources)

ESG: Environmental, Social, and Governance

EU: European Union

EUETS: EU Emissions Trading System

Eurostat: Statistical Office of the European Union

Fe: Iron

GBFS: Ground Granulated Blast Furnace Slag

GCGA: Global Cement and Concrete Association

GJ: GigaJoule

H: Hydrogen

HCl: Hydrogen Chloride

HF: Hydrogen Fluoride

Hg: Mercury

HHV: Higher Heating Value

IEA: International Energy Agency

Indocement: PT Indocement Tunggal Prakarsa Tbk.

ISO: International Organization for Standardization

Jabodebek: Jakarta, Bogor, Depok, and Bekasi (combined area name)

Kemenkeu RI: *Kementerian Keuangan Republik Indonesia* (Ministry of Finance of the Republic of Indonesia)

Kemenperin: *Kementerian Perindustrian Republik Indonesia* (Ministry of Industry of Indonesia)

KLHK: *Kementerian Lingkungan Hidup dan Kehutanan* (Ministry of Environment and Forestry)

kW: Kilowatt

LHV: Lower Heating Value

LSI: *Lembaga Survei Indonesia* (Indonesia Survey Institute)

MBT: Mechanical Biological Treatment

MC: Moisture Content

Mg: Megagram (metric ton)

MJ/kg: MegaJoule per kilogram

MJ: MegaJoule

mm: millimeter

MSW: Municipal Solid Waste

N: Nitrogen

NH3: Ammonia

Ni: Nickel

Nm^3: Normal cubic meter

NOx: Nitrogen Oxides

O: Oxygen

O_3: Ozone

Opex: Operating Expenditure

Pb: Lead

PCB: Printed Circuit Board

PCDD/F: Polychlorinated Dibenzodioxins/Dibenzofurans

PPP: Public-Private Partnership

RDF: Refuse Derived Fuel

RDFP: RDF Production Plant Model

S: Sulfur

Sb: Antimony

SO_2: Sulfur Dioxide

Statistisches Bundesamt: Federal Statistical Office (Germany)

TEQ: Toxic Equivalency Quotient

TJ: Terajoule

TOC: Total Organic Carbon

TVOC: Total Volatile Organic Compounds

U.S. Census Bureau: United States Census Bureau

VAT: Value Added Tax

VDZ: Verein Deutscher Zementwerke (German Cement Works Association)

VOC: Volatile Organic Compounds

wt.: Weight

WtE: Waste-to-Energy

1. Introduction & Objectives

Cement is an essential building material known for its durability and versatility. It serves as a fundamental component widely used in the construction and development of infrastructure, playing a significant role in advancing human life. According to Cembureau (2023), the global cement production capacity in year 2022 stood at 4.3 billion Mg and is expected to continue increasing in the future. However, this upward trend in cement production will likely intensify the cement industry's challenges in reducing CO_2 emissions. The global cement industry faces at least three global issues requiring continuous solutions. The first challenge is reducing global CO_2 emissions from the cement industry. The second challenge involves production efficiency, encompassing cost efficiency, natural resource efficiency, and fuel usage. And the third challenge pertains to the implementation of economic circularity. Previous research on CO_2 emissions reduction in the cement industry has also led to savings in purchasing materials required during cement production (Rootzén & Johnsson, 2017). Therefore, the cement industry bears significant responsibility for climate protection, particularly in addressing CO_2 emissions reduction and preserving natural resources (Salamanova et al., 2020; VDZ, 2020).

Similar to global challenges, the cement industry in Indonesia also faces similar issues, including production efficiency, CO_2 emissions reduction, and concerns regarding sustainable business practices. Indeed, according to the Industrial Ministry of Indonesia, Kemenperin, (2022), cement production in Indonesia contributes to 28% of the country's CO_2 emissions. Consequently, the cement plant under investigation, owned by Indocement, one of the leading cement companies in Indonesia with a market share of 27.3% in 2024, is located in Citeureup, West Java (Indocement, 2024). The company is actively working to address environmental challenges with the goal of becoming a more sustainable cement producer. One of the methods is the utilisation of alternative fuels (AF), with a target to achieve a 50% substitution rate for coal by the year 2030. This target corresponds to approximately 4,800 Mg per day of AF. To meet this target, progress has already been made. By 2023, the substitution rate had reached 18.3%, equating to about 1,000 Mg per day of AF. In 2024, it is expected to increase to 23%, which corresponds to around 1,600 Mg per day of AF. By 2025, the substitution rate is projected to reach 27%, equivalent to approximately 2,000 Mg per day of AF (Indocement, 2024).

Another pressing issue is concerning municipal solid waste (MSW) that must be addressed. According to Valavanidis (2023), there are several global problems related to MSW management, such as landfills, less waste separation, and population growth. This issue also arises in Indonesia, producing approximately 69 million Mg of MSW annually (KLHK, 2023). Traditional MSW management practices remain prevalent, with an astonishing 80-90% of MSW ending up in landfills. However, many of these landfills have reached full capacity and are overburdened, leading to serious health and environmental concerns for the local community. This problem is particularly acute in the densely populated economic sector of the metropolitan region encompassing Jakarta, Bogor, Depok, and Bekasi, which collectively generates about 14,500 Mg of MSW per day in its raw or wet base condition, predominantly disposed of in landfills (BPS Jakarta, 2020; KLHK, 2023). Since 2008, the Indonesian Government has had a legal enforcement instrument known as Law Number 18 of 2008 on Waste Management (BPKRI, 2008). This situation is governed by regulations that mandate systematic, comprehensive, and sustainable activities encompassing MSW reduction and handling. Under these legal frameworks, the government and local authorities are responsible for ensuring proper waste management practices that are environmentally conscious and legally compliant. However, implementing these practices has yet to reach optimal effectiveness.

As part of assisting the Indonesian government's MSW management policies, one approach is the technological conversion of MSW into refuse-derived fuel (RDF) as an AF. This method involves producing RDF from MSW that undergoes mechanical treatments such as sorting, refining, shredding, and drying (Srivastava, 2021). This RDF shares characteristics with conventional fuel as it predominantly consists of the combustible fractions of MSW (Paszkowski et al., 2020a). For instance, in Europe and globally, cement manufacturers currently use RDF as a common AF to replace coal, aiming to optimise fuel costs (Paszkowski et al., 2020). Therefore, the utilisation of RDF presents a convergence of solutions between cement production challenges, including production efficiency, CO_2 emission reduction, and the implementation of sustainable business practices with MSW management issues. This signifies a promising cross-sectoral solution that has the potential to address two distinct yet interconnected challenges. Also, RDF presents several advantages, such as its use as an alternative energy source in the cement sector and the flexibility to be produced in one facility and transported for use in various industries, including power plants (Kothari & Thorat, 2014). The reduction of CO_2 emissions has positive impacts on the environment and the industry. Processing MSW into RDF for AF can be a collaborative solution between cement producers and the government, particularly at the city level. Therefore, considering the context outlined above, the main objective of this study is to explore the use of RDF as an AF in the cement industry across the four cities of Jakarta, Bogor regency, Depok, and Bekasi. These cities are collectively referred to as Jabodebek for this research. To address this aim, the title chosen for the study is "Viability of Refuse-Derived Fuel (RDF) from Municipal Solid Waste (MSW) as a Sustainable AF for the Cement Plant in Citeureup, West Java, Indonesia."

Based on the background provided, the primary goal of this study is to develop a sustainable MSW management system that incorporates the production and use of RDF. This effort is designed to be consistent with national MSW management policies and aims to support the operations of the cement plant in Citeureup. The detailed objectives are as follows:

1. To evaluate the MSW characteristics from Jabodebek as a source for RDF.
2. To establish a pilot RDF production plant to assess its performance and gather best practice experience.
3. To determine a suitable proposal for RDF Supply for the Cement Plant.
4. To assess the total heat substitution generated from the utilisation of RDF from the cities surrounding the Cement Plant.
5. To assess the potential for reducing CO_2 emissions by utilising RDF from the four cities (Jakarta, Bogor Regency, Depok, and Bekasi) around the Cement Plant.
6. To estimate the potential for air emissions due to the utilisation of RDF from the four surrounding cities.

Subsequently, the hypotheses of this study are as follows:

1. MSW from Jakarta, Bogor, Depok, and Bekasi can be converted into RDF through optimised drying, making it a viable alternative fuel for cement plants in Citeureup, West Java, aiming for a 50% coal substitution by 2030.

2. RDF production at cement plants using hot gas for drying is the most cost-effective method.

3. Utilising RDF from MSW in cement plants significantly reduces CO_2 emissions compared to coal, supporting sustainability goals.

4. The utilisation of RDF from MSW in cement plants will increase air pollutants but will meet emission standards and can be controlled with appropriate technology.

2. Integrating on Municipal Waste Management as AF in Cement Industry

2.1 Typical Cement Production Process

Cement is a common building material that has been in use from ancient to modern times; its use originated from the Egyptians' gypsum-based formula for the pyramids and was developed by the Romans with volcanic materials from Vesuvius, which was further refined by the Greeks, culminating in significant progress by the 18th century (Pérez et al., 2024). Further exploration into the hydraulic characteristics of clay-bearing limestone has led to significant improvements in cement, including the enhancement of hydraulic lime with added silica and the creation of cement from a combination of limestone and clay (Anhar et al., 2016; Pharma & Zainul, 2016). The development of Portland cement in the 19th century, made by calcining a mix of clay and limestone into clinker, significantly advanced cement production and set the stage for current manufacturing techniques (Ermilova et al., 2020).

Portland cement is defined as a hydraulic cement produced by grinding clinker, primarily composed of calcium silicate hydrates and additional materials (ASTM, 2020). Generally, there are four types of cement raw materials used, namely limestone, clay, iron sand, and silica sand, with limestone being the dominant raw material comprising 50-90% of the raw material content (Chatterjee, 2018; Saleh & Eskander, 2020). As for the fuels used, the dominant conventional fuel is coal, with a Lower Heating Value (LHV) range of 15-35 MJ/kg, and there are minor fractions such as gas and liquid-based fuels (Nunes et al., 2021). Moreover, AFs are being utilised as replacements for coal to augment the fuel mix. These substitutes typically possess comparatively lower quality and exhibit substantial variability, with their LHV spanning from 5 to 30 MJ/kg (Tan et al., 2023). Figure 2.1 below is illustrating the AF substitution from selected average global cement companies.

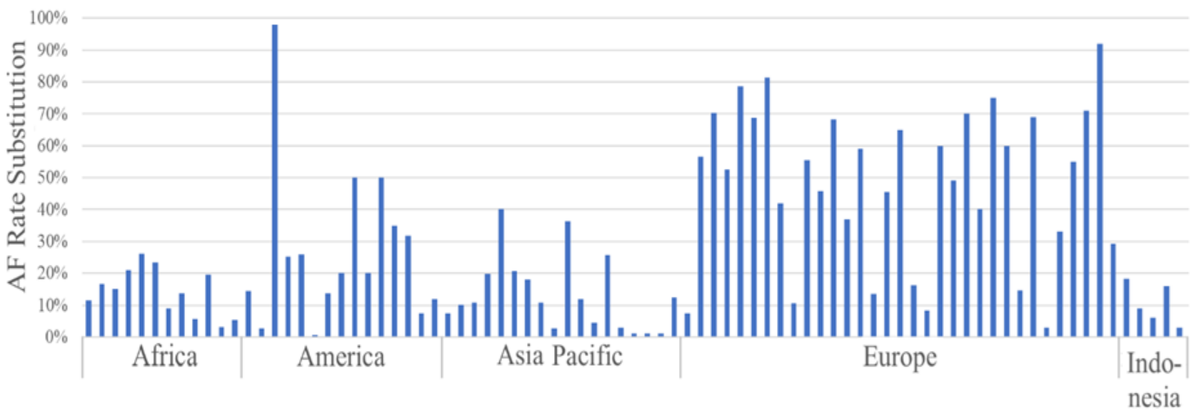

Figure 2.1 AF Rate Substitution from Selected Global Cement Companies in 2023.
Adapted from Heidelberg Material, (2024)

Based on Figure 2.1, the AF rate in Africa region ranges from 3-26%, in America from 1-97%, in Asia Pacific (APAC) from 1-40%, in Europe from 7-92%, and in Indonesia from 3-18% (Heidelberg Material, 2024). America and Europe have higher AF rate utilisation than other regions, including Indonesia. In the future, it is anticipated that different regions will also increase their AF rates significantly.

In cement production, there are two main methods being used, a) the wet process mixes raw materials with water to form a slurry for uniformity, and b) the dry process, more prevalent in modern times, uses raw materials as they are. The dry process is favoured for its cost-effectiveness, efficiency, and more straightforward maintenance (Mamlouk & Zaniewski, 2018). Figure 2.2 below outlines the typical dry process of cement manufacturing, which is the commonly used method in modern times.

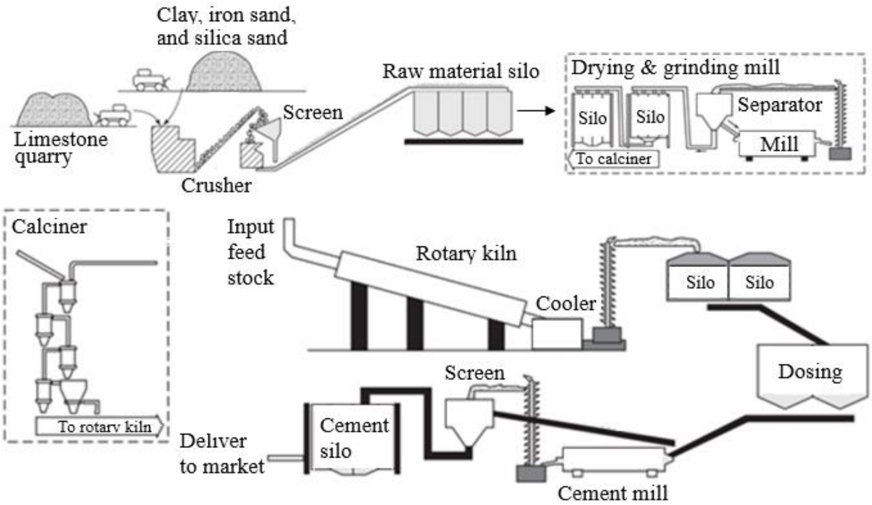

Figure 2. 2 Dry Process of Cement Manufacturing
Figure taken from Mamlouk & Zaniewski, (2018)

Next, an explanation of the process begins with the quarrying stage, where the basic cement materials are limestone, clay, iron sand, and silica sand. Those raw material are extracted from nature and crushed. These raw materials are processed using heavy machinery and transported to the cement plant (Egbe & Olugboji, 2016; Peinado et al., 2011). Subsequently, the materials that have been crushed are placed into a raw material silo. A silo is a structure for storing bulk materials, and in this context, it holds the raw materials used in cement production (Widyanto et al., 2020).

Once the raw materials are in the silo, they proceed to the drying and grinding mill stage. This equipment is designed to grind and dry raw cement and alternative raw materials, reaching temperatures of up to 300°C. Generally, this stage involves the reduction of limestone, clay, silica sand, and iron sand from sizes of 5-7 cm to fine dust particles of 0-9 μm. Drying simultaneously decreases the materials' moisture content. This machinery operates around the clock, 24 hours a day (Afrina, 2018; Setiyana, 2007). The process then moves on to the calciner, which can also function as a Preheater or Precalciner. The calciner preheats raw materials, starting the calcination reaction to transform calcium carbonate ($CaCO_3$) into calcium oxide (CaO) before they enter the kiln. The exit gas temperature of the calciner is maintained between 870°C and 950°C, a temperature range necessary for the calcination of limestone (Liandari et al., 2022; Tiara & Anugrah, 2022). During operation, the process temperatures are suitable for utilising AFs in addition to coal (Alujas et al., 2015). The next step is rotary kiln that plays a pivotal role in the combustion, mixing, and decomposition of kiln feed, a mix of limestone, clay, silica sand, and iron sand, transforming it into clinker. This artificial rock, clinker, is formed from the raw meal through high-temperature processes inside the kiln, reaching around 1450°C (Habert et al., 2020; Salas et al., 2016; Xu et al., 2012). During the heating process inside the rotary kiln, simultaneous physical and chemical reactions occur, along with interactions between molecules that form clinker compounds. Inside the rotary kiln, compounds such as C3S, C2S, C3A, and C4AF are formed (Wijayanto, 2022). After exiting the rotary kiln, the hot material proceeds to the clinker cooler, where the clinker undergoes rapid cooling from an initial temperature of 1400°C to 100-200°C, leading to the formation of semi-finished product crystals called clinker. Fans blow air into the clinker from beneath the multilane cooler during cooling. The clinker cooler's operation is driven by hydraulic cylinders that move the clinker to the clinker silo (Prasetiyo et al., 2023).

The subsequent step is grinding in the cement mill or finish mill. Its objective is to pulverize the blend of clinker together with supplementary materials such as gypsum, fly ash, trass, or other admixtures into a fine dust that aligns with the precise demands of the intended cement specifications. Afterwards, this cement is stored in a cement silo. The final step involves the cement that meets the specifications being packed and delivered using packing machines into various types of packaging such as sacks, jumbo bags, bulk trucks, and others, in accordance with market demand (Zheng et al., 2020).

Cement production is an international enterprise, with various areas of the world serving as key hubs for manufacturing. These prominent regions are spread across the globe, with Asia, especially China, prominently leading the surge in production. The continued urbanization and infrastructure development within Asia suggest that production will continue upward. As of year 2022, the global cement industry achieved an impressive total output of approximately 4.3 billion Mg (Cembureau, 2023). This substantial figure is largely attributed to the production efforts of the top six cement-producing nations, including China, India, Vietnam, the United States, Turkey, Brazil, and Indonesia. Together, these countries contributed to around 70% of the total global production within the year, showcasing their significant roles in meeting the world's construction needs. Their combined efforts underline the strategic importance of these countries in maintaining the supply chain of one of the most crucial materials in the construction sector (Statista, 2023; Shen et al., 2015; Tkachenko et al., 2023).

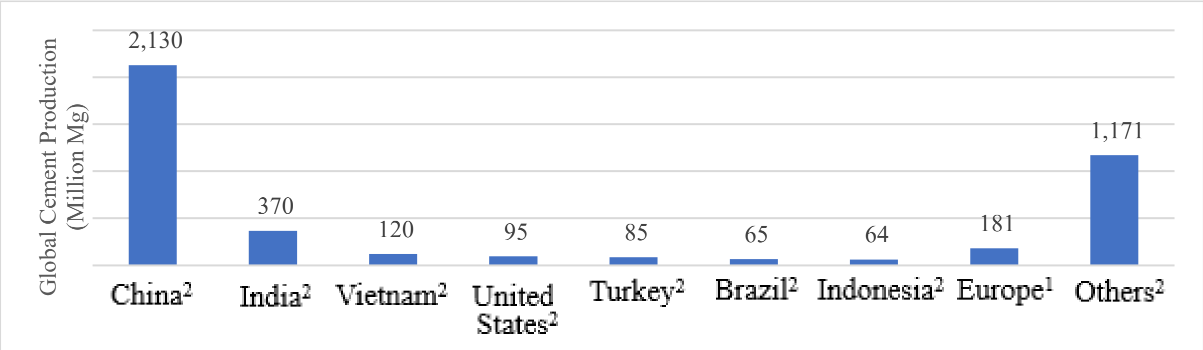

Figure 2.3 Global Cement Production 2022 in Million Mg
Figure taken from [1]Cembureau (2023) and [2]Statista (2022)

Figure 2.3 exhibits that in 2022, Indonesia's cement industry achieved a remarkable production milestone, hitting 64 million Mg. Within this robust industry, Semen Indonesia emerges as the dominant player, securing a 43% market share, while Indocement trails behind as the second-largest producer, maintaining around 27% of the market share (ASI, 2023; Cemnet, 2023).

2.2 Cement Industry Contribution in Global CO_2 Emission

In 2022, it was indicated that the cement production process emits 2.3 billion Mg of CO_2 annually, which accounts for approximately 7-8% of global CO_2 emissions (Fennell et al., 2022; Lehne & Preston, 2018). One of the sources of these emissions primarily originates from the calcination process of limestone during clinker production. Approximately 35-40% of clinker CO_2 emissions stem from energy usage in cement production, while the remaining emissions are predominantly released from chemical reactions occurring when limestone is heated (McKinsey & Co., 2022; Shanks et al., 2019). The significant emissions from the cement industry can be attributed to the high global production and demand for cement, which is expected to maintain an upward trend (Hasanbeigi et al., 2012; Stafford et al., 2016). Below is Figure 2.4 that explains the sources of CO_2 emissions in the cement production process.

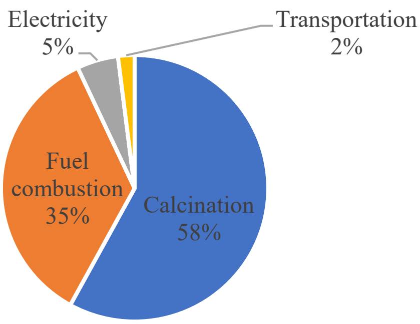

Figure 2.4 Sources of CO_2 Emissions in the Cement Production Process
Figure taken from Andrew (2019) and IEA (2022)

Therefore, GCCA has launched a net zero country roadmap accelerator program, which assists national cement and concrete industries in creating their comprehensive roadmaps on a global scale. The global ambition to eradicate these emissions by 2050 necessitates that the industry, across all regions, hasten the reduction of CO_2 emissions. The accelerator program is instrumental in pinpointing local obstacles to decarbonization and recommending essential actions. These national roadmaps are designed in accordance with the fundamental tenets of the GCCA global roadmap, which targets reaching zero emissions by the year 2050, with interim milestones set for year 2030 (GCGA, 2023). Meanwhile, the cement industry is the largest contributor to CO_2 emissions in Indonesia's industrial sector. Eight sub-sectors within the industrial domain contribute to these emissions. Figure 2.5 below illustrates the contribution of the industrial sector to CO_2 emissions in Indonesia.

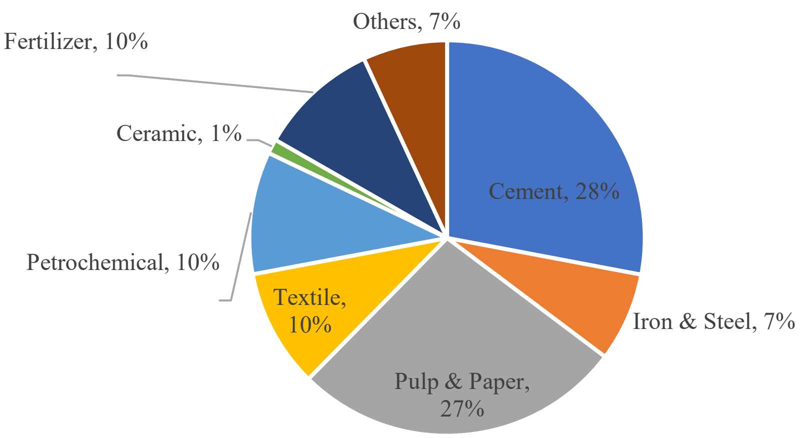

Figure 2.5 Industrial Sector Contributing to CO_2 Emissions in Indonesia 2022
Figure taken from Kemenperin (2022)

2.3 Implementation of ESG and Circular Economy

The cement industry naturally implements environmental, social and governance (ESG) and circular economy principles due to the need for resource efficiency in raw materials and fuel, reduction of CO_2 emissions, and compliance with governmental regulations and market demands (Cembureau, 2023; Rajabipour et al., 2015). Figure 2.6 depicts the implementation of this process within the cement industry.

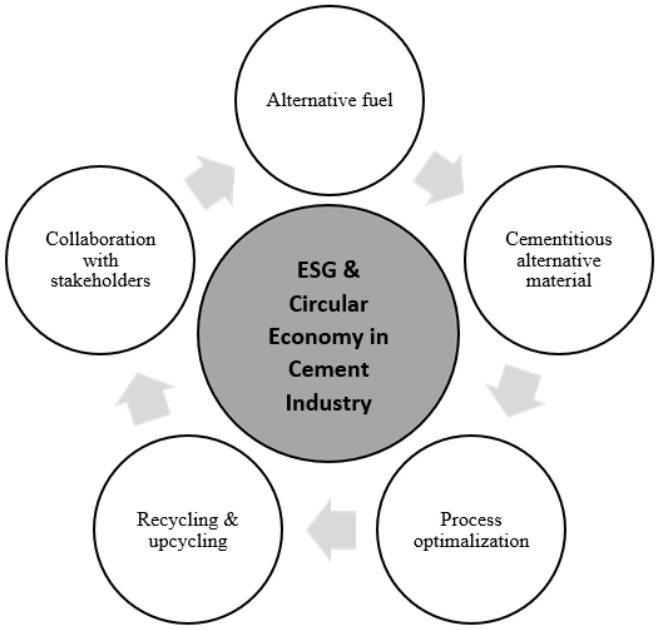

Figure 2.6 ESG and Circular Economy Implementation in Cement Industry (adapted from: Scrivener et al., 2018; Singh et al., 2017)

Using AFs as coal substitution in the cement industry is a critical strategy for reducing dependency on fossil fuels, lowering operational costs, and minimizing the carbon footprint from the cement production process. Additionally, RDF utilisation assists governments and adds value by converting MSW into energy-rich fuel while helping the cement industry achieve sustainability goals (Rada, 2019). The next strategy is the application of alternative cementitious materials, such as fly ash and slag, as substitutes for clinker, which can reduce the calcination process and subsequent CO_2 emissions. Both fly ash, a residual from coal combustion in power plants, and slag, a byproduct of steel production, have the potential to partially replace clinker in cement manufacturing, offering a sustainable solution to lowering the industry's carbon footprint (Fang et al., 2018). The following step is optimising processes to reduce energy, power, and production losses. Typically, cement plants will implement more efficient procedures and the latest technology. Aspects that need to be considered include specific targets for energy and power usage, compliance with emission limits, and the percentage of raw material utilisation (Reis et al., 2021).

Additionally, the cement industry can integrate concepts of recycling or upcycling by reprocessing materials such as damaged or unused concrete. This material can be crushed and reused as aggregate in the production of new cement (Wang & Zhang, 2018). Similarly, the reuse of packaging waste from industrial and commercial sectors can be part of ESG initiatives and Circular Economy programs (Sarc & Viczek, 2023).

Moving forward involves stakeholder collaboration, focusing on concepts like extended producer responsibility (EPR) and CO_2 credits. These are prime examples of effective partnerships between private entities and governments. Implementing EPR can motivate the related producers to explore innovative product designs that reduce waste, create recyclable materials, and prevent landfill disposal. Here, the cement sector leverages this waste as RDF or as an AF. Several studies indicate that EPR can address resource efficiency and reduce industrial waste (Verawati, 2022). EPR is highly emphasized for producers and has become mandatory. For instance, it is regulated by the EP (2018), Directive (EU) 2018/851. In Indonesia, it is governed by the Basic Law No. 18 of 2008 concerning Waste Management (BPKRI, 2008). Next is the carbon credit system. The European Union (EU) has one of the largest emission trading schemes, known as the EU Emissions Trading System or EUETS (EP, 2003). Meanwhile, in Indonesia, the regulation is outlined in Presidential Regulation No. 98 of 2021 regarding implementing the carbon economy and its trading (GoI, 2021). The average carbon price in Europe in March 2024 is 60 Euros/Mg of CO_2 (EC, 2024).

2.4 State of the Art of AF Production and Utilisation in Cement Industry

Utilising AF in cement production boosts cost savings and offers environmental and economic benefits. It reduces landfill use, cuts greenhouse gas emissions, and aids in the sustainable development of the cement sector within the national energy and waste management strategy (Bocheńczyk et al., 2021). When associated with MSW management, using RDF as an AF within the cement industry is highly effective in mitigating the negative impacts of MSW generation. This contributes positively to urban health and promotes the application of technology that is not only environmentally friendly and efficient but also contributes to cost-effective production and the enhancement of quality improvement technology (Itsarathorn et al., 2022). Figure 2.7 below shows AFs available to the cement industry.

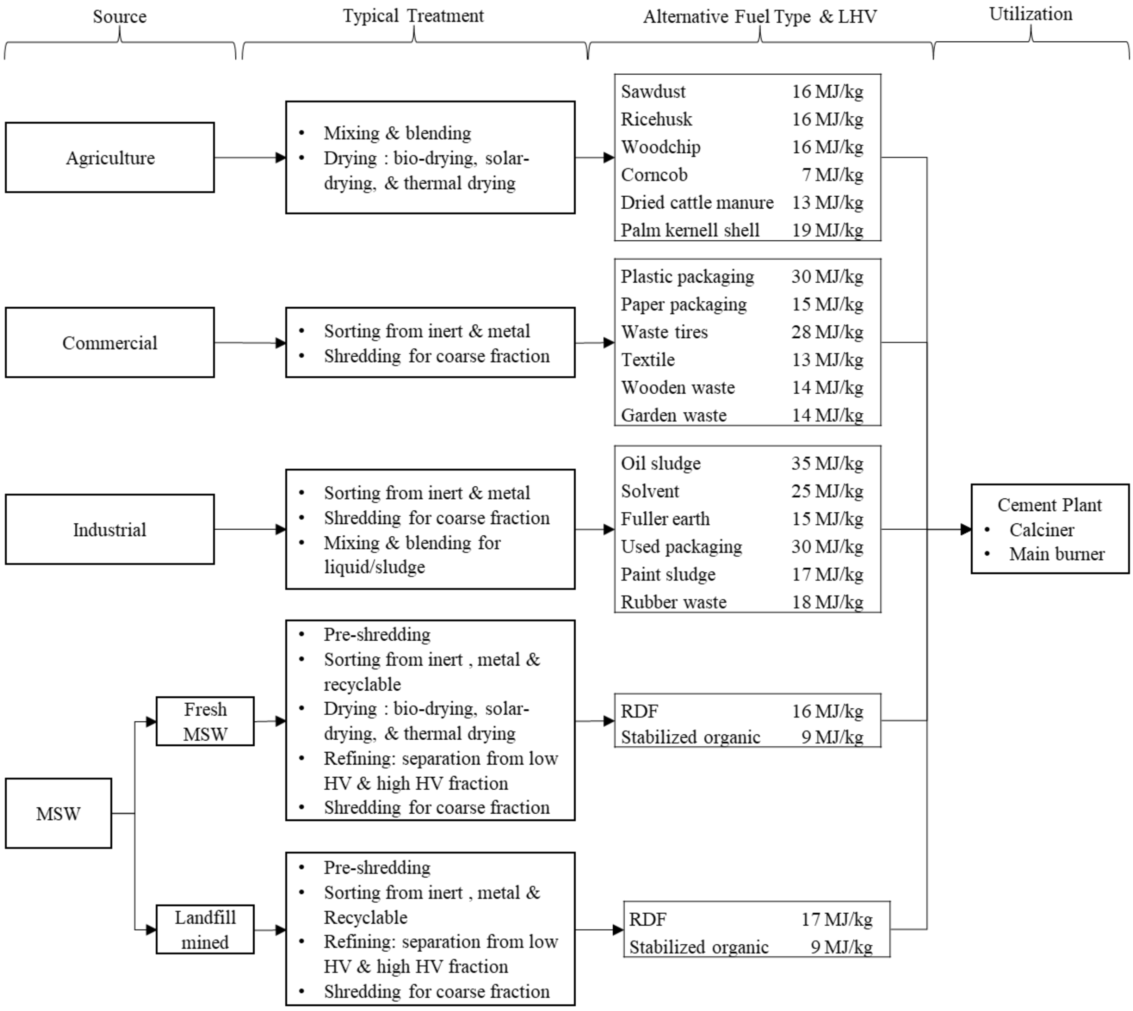

Figure 2.7 Typical Alternative Fuel Sources Available to Cement Industry
Figure taken from Indocement, (2024); Kumar & Patel (2014); Kusuma et al., (2020); Zieri (2019)

The option for pre-shredding is applied to both fresh MSW and materials sourced from landfills, aiming for a size of 200-300 mm. It shreds and opens packaging. A bag-opener can be combined with it for efficiency. Both can be used together, or just the pre-shredder, which also opens bags effectively (Mavropoulos, 2015). The next option is mixing and blending, which can be applied to agricultural products such as sawdust, rice husks, other forms of biomass, and liquid and sludge wastes. Mixing can be conducted simply by using wheel loaders or specialized equipment like rotary mixers. This step is beneficial for homogenizing quality, increasing heating value, and reducing moisture content (Rajput et al., 2020; Wang et al., 2020).

The next stage is the sorting process, where manual selection is the commonly used method. This involves workers hand-picking recyclable materials and discarding unwanted components. An alternative method employs a Trommel screen, which sorts materials by size; this can be further enhanced with the use of a magnetic separator (Worrell & Vesilind, 2012). Generally, for the processing of particularly wet MSW using a trommel, larger screen size is preferred, at times up to 80 mm, to prevent the blockage issues commonly caused by the smaller screens size. The treatment process' subsequent phase involves drying the AF, which is essential for lowering moisture and enhancing energy value. This step is vital for high-moisture AF, preparing it for efficient combustion (Zamrudy et al., 2019). This is particularly applicable for AF from agricultural sources and fresh MSW, which typically exhibit a moisture content ranging between 30-70% (Feltrim et al., 2021; Smith et al., 2020). However, when sourcing AF from commercial, industrial and landfill, which usually contain lower moisture in the range of approximately 10-30%, drying may not be necessary (Kusuma et al., 2020; Rhoshenia et al., 2021; Tihin et al., 2023).

The first drying option, bio-drying is a drying method that utilises microbial heat generation during aerobic decomposition to lower moisture in organic MSW or agricultural waste. This mechanical biological treatment (MBT) method diminishes waste size and boosts energy content (Quan et al., 2023). Solar drying is the next possible option, using sunlight to lower moisture, enhances waste's energy value and reduces its size and mass, which is ideal for tropical regions (Kumar et al., 2017). Thermal drying, the final drying method, uses heat to decrease waste moisture, often from electricity or residual heat. Different dryers like rotary, belt, and box are chosen based on the waste properties (Kalogirou, 2018). Table 2.1 below shows the key performance of these 3 drying methods.

Table 2.1 Key Performance for the Selected Drying Methods

Option	**Drying period**	**Operating Temperature (°C)**	**MC Reduction (%)**
Bio-drying	7-33	30-70	20-50
Solar-drying	2-9 days	22-75	40-60
Thermal Drying	30 – 290 minutes	6-200	20-70

Table adapted from Tun & Juchelková, (2019)

The ensuing step is the refining stage, which separates larger items such as plastic, paper, and wood from smaller materials like organic matter, sand, and pebbles. A trommel screen with a 30-50 mm mesh is used for this purpose (Velis & Brunner, 2013). The other option is a ballistic separator, a specialized machine for sorting waste based on the shape and size with dynamic paddles, distinguishing heavier or 3D objects from the lighter ones (López et al., 2019). The process yields two types of outputs: larger, lighter materials with more energy, and smaller, heavier components suitable for compost or low-grade RDF, with an LHV of 8 to 13 MJ/kg (Raclavska et al., 2011).

Subsequently, refinement processes include magnetic separators for ferrous metals, wind-shifters and cyclones for density-based separation, Eddy current separators for non-ferrous metals, and techniques for sorting recyclables manually and optically (Fei et al., 2018). For a more sophisticated advancement, AI robots are used to enhance the separation and recycling, thus providing a quicker, more efficient alternative to manual and optical sorting methods (CNR, 2023).

In harnessing AF for cement, size is a key determinant of combustion efficiency. The shredding process can shred it down to a target smaller size, like 50-80 mm. Regarding the utilisation of RDF, the particle size is crucial. Smaller particle sizes increase the surface area, facilitating a faster combustion process. Thus, the fine shredding process becomes vital in creating high-quality RDF, which has an LHV of 12-20 MJ/kg and a finer size, by ensuring that the size of the material is reduced to the ideal size for efficient burning (Shumal et al., 2020; Velis & Brunner, 2013). As an essential addition, proper storage facilities are vital for the treatment of AF, to ensure proper raw materials storage considering their weight and density, typically for two days. Additionally, a leachate drainage system is crucial for handling high-moisture materials and adhering to safety standards (Infiesta et al., 2019). Figure 2.8 depicts a mass flow analysis for sources treated mechanically, reflecting the know-how of service providers and Indocement's use of AFs from waste. It clarifies the treatment's inputs/outputs and highlights mechanical treatment's role in enhancing waste quality for AF use.

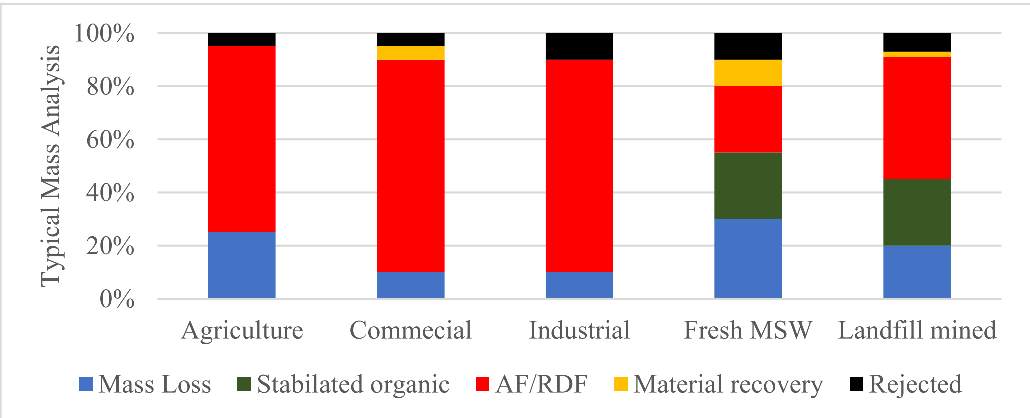

Figure 2.8 Typical Mass Analysis of Mechanical Treatment for Each Source

Mass loss in RDF production refers to the reduction of water and volatile substances. Stabilised organic material, typically used as RDF, is the dried organic portion. AF/RDF is the processed end product. Material recovery involves reclaiming valuable items like plastics, metals, and glass. Rejects are non-combustible materials like stones. The data depends on the AF's source, indicating possible variations in mass flow, even with identical technology. AF facilities must tailor outputs to meet off-taker standards, which vary based on the end user's needs and acceptance levels. The RDF specifications for the cement industry is outlined in Table 2.2.

Table 2.2 RDF Specification

Parameters	Unit	Europe (ISO 21640:2021)[1]					Germany[4]	Indonesia[2,3]
		Classes						
		1	2	3	4	5		
LHV	MJ/kg	≥25	≥20	≥15	≥10	≥3	-	≥12.5
Cl	% (db.)	≤0.2	≤0.6	≤1.0	≤1.5	≤3	-	≤0.75
S	% (db.)	-	-	-	-	-	-	≤1
Hg	median mg/MJ	≤0.02	≤0.03	≤0.05	≤0.10	≤0.15	-	
	80th percentile mg/MJ	≤0.04	≤0.06	≤0.10	≤0.20	≤0.30	-	
	mg/kg (db.)	-	-	-	-	-	≤1.2	≤1.2
Cd	mg/kg (db.)	-	-	-	-	-	≤9	≤70
Pb	mg/kg (db.)	-	-	-	-	-	≤200-400	≤100
Cr	mg/kg (db.)	-	-	-	-	-	≤120-250	≤1,500
Ni	mg/kg (db.)	-	-	-	-	-	≤100	≤1,000
Cu	mg/kg (db.)	-	-	-	-	-	≤300-700	≤1,000
MC	% (ar.)	-	-	-	-	-	-	≤20
Size	mm	-	-	-	-	-	-	≤50

Table adapted from ([1]CEN, 2021a; [2]Kemenperin, 2017; [3]KLHK, 2021; [4]MUNLV, 2005)

The Table 2.2 outlines RDF standards in Europe and Indonesia. Europe's standards, per ISO 21640:2021, are split into five classes based on Lower Heating Value (LHV), with class 1 (>25 MJ/kg) being the highest and class 5 (>3 MJ/kg) the lowest. Higher classes have stricter chlorine (Cl) limits. Indonesia sets its LHV standard at >12.5 MJ/kg, not aligning with any European class, and caps sulphur (S) content at <1% (db.). Indonesia also specifies limits for mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), and copper (Cu), unlike Europe's class-based approach. Indonesia mandates RDF moisture content to be under 20% (ar.) and particle size below 50 mm. The standards guarantee RDF suitability for waste management. Compliant RDF is utilised in cement production, with the flexibility of these standards hinging on supplier and producer agreements. The utilisation of RDF by Indocement is depicted in Figure 2.9.

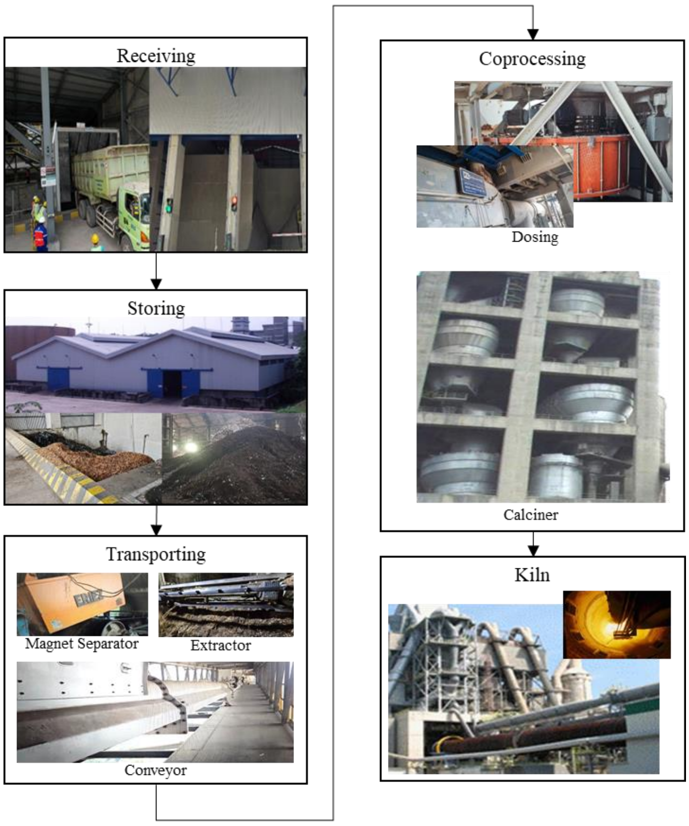

Figure 2.9 AF Utilisation in Indocement
Figures taken from (Indocement, 2024)

Typically, AF is delivered to Indocement's plants via dump trucks and then unloaded into a receiving pit or bunker. The AF is then stored, usually maintaining a 2-3-day supply in the storage area. Following storage, AF is transported to the calciner area with the help of an extractor and further assisted by a magnetic separator to prevent ferrous metal contamination. The extractor facilitates the transfer of AF from storage onto a conveyor. Next, the conveyor carries AF to the dosing facility to regulate the AF feed rate into the calciner. Within the calciner, AF is burned at a continuous temperature range of 850-1,000°C. Subsequently, the hot gases from the combustion process are directed to the kiln, along with coal, to ensure that the materials' temperature reaches 1,200-1,450°C. Table 2.3 describes the general requirements of AF combustion for each calciner operated by Indocement.

Table 2.3 General Requirements of AF Combustion for RDF in Indocement

Calciner Type	AF Size	MC	Capacity
In-line Calciner	<50-130mm, <50-80mm (optimum), 2d	≤ 20%	up to 400 Mg/day
Combustion chamber	<50-130mm, <50-80mm (optimum), 2d	≤ 30%	up to 960 Mg/day
Hotdisc	<50-300mm, 2d,3d	≤30%, less volume ≤ 45%	up to 960 Mg/day

(Source: Indocement, 2024)

3. Current Situation of MSW Management in Indonesia and Jabodebek

3.1 Overview of MSW Management in Indonesia

Indonesia is an archipelagic country located in Southeast Asia, spanning an area of 1.919 million km², which makes it the 15th largest country in the world. As of 2023, it is estimated to have a population of 281.5 million (BPS, 2023b; USBC, 2023). Figure 3.1 illustrates the per capita generation of MSW in Indonesia compared to a selection of other countries.

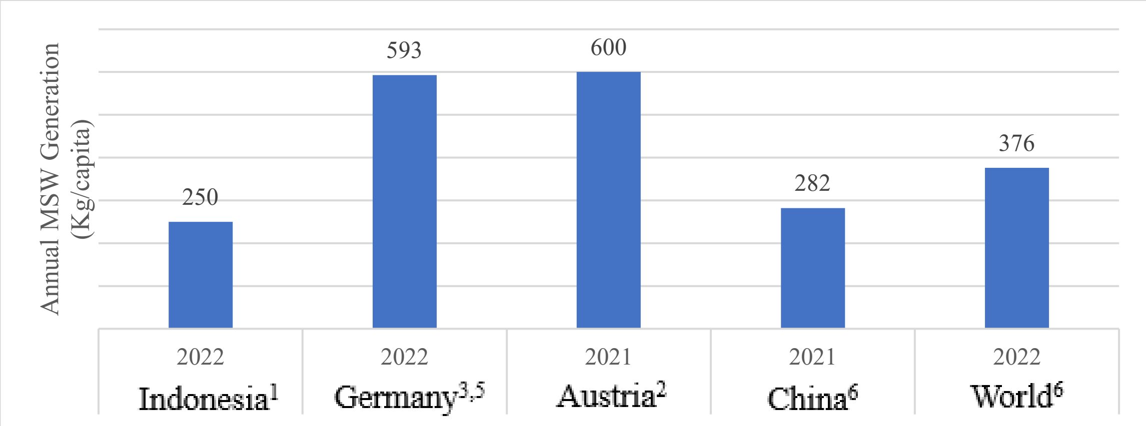

Figure 3. 1 Annual MSW Generation in Indonesia and Selected Countries
([1]BPS, 2023b; [2]EEA, 2023; [3]Eurostat, 2023; [4]KLHK, 2023; [5]Statistisches Bundesamt, 2023; [6]World Bank, 2023b)

Indonesia, classified as a lower-income country, has a smaller per capita generation of MSW compared to higher-income nations like Germany and Austria, indicating a correlation between socio-economic status and MSW generation (Velis et al., 2023). According to KLHK (2023), the estimated annual increase in MSW generation is around 1.13%, with a total of 68.9 million Mg of MSW generated in Indonesia in 2022. Figure 3.2 illustrates the breakdown of MSW in Indonesia compared to other countries.

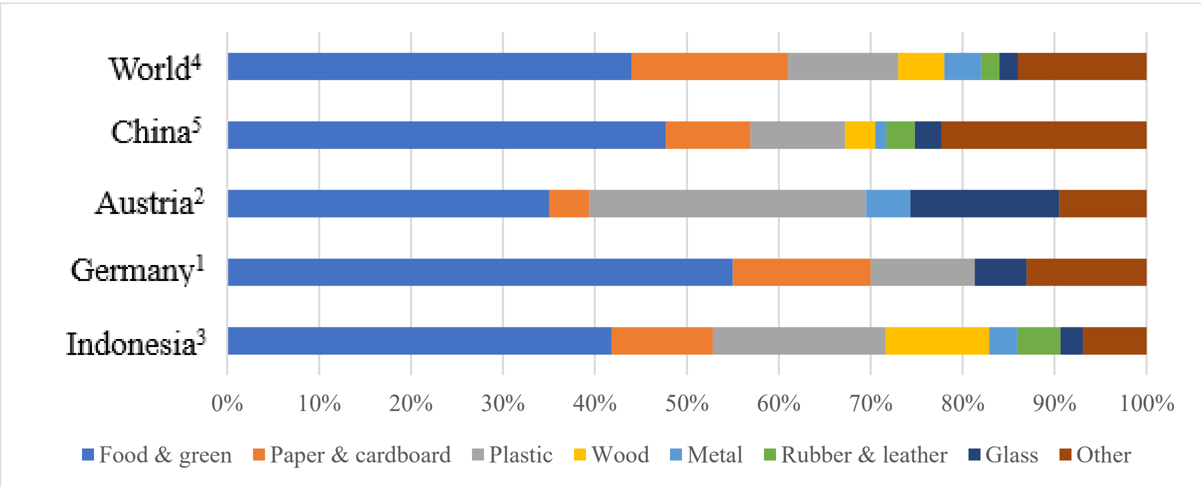

Figure 3. 2 Waste Composition in Indonesia and Selected Countries
([1]BMUV, 2023; [2]Kladnik et al., 2024; [3]KLHK, 2023; [4]World Bank, 2023c; [5]Zhu et al., 2021)

According to Figure 3.2, food and green waste, paper, and plastic fractions persist as the predominant contributors to global MSW generation, largely driven by the high production and consumption rates related to food and its associated packaging materials. Furthermore, Figure 3.3 compares the recycling rate of MSW between Indonesia and several other countries.

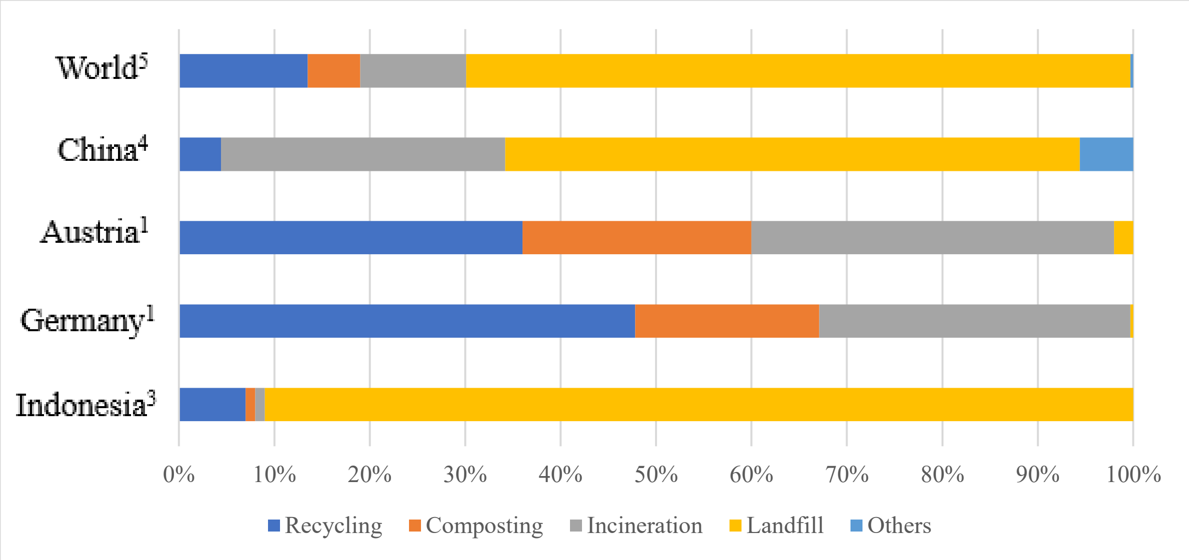

Figure 3. 3 MSW Management Rate in Indonesia and Selected Countries
([1]EEA, 2022; [2]KLHK, 2023; [3]Kurniawan et al., 2022; [4]WMW, 2023; [5]World Bank, 2023c)

In Indonesia, recycling activities mainly focus on valuable materials, such as bottle packaging, 3D plastics, metal, and glass, retrieved from mixed MSW piles (Wararatna & Subekti, 2022). Meanwhile, the remaining MSW, which makes up nearly 90%, is typically disposed of in landfills. Conversely, in Germany, a country with the highest recycling rate, recycling is facilitated because collected waste is already well-sorted (BMUV, 2023). The Indonesian government has encouraged the public to reduce MSW and increase the recycling rate through educational outreach and strict sanctions (Romdoni et al., 2022). However, there has not yet been a significant shift in the societal and cultural attitudes of the community towards MSW management, starting from proper waste sorting practices (Hapsah, 2022).

A well-structured legal framework in Indonesia is critical for preserving public health and environmental quality, particularly in managing MSW. This framework includes specific provisions for handling RDF to ensure MSW is safely and responsibly converted to energy, as shown in Figure 3.4 on the subsequent page. This representation guides policymakers and industry practitioners in implementing sustainable MSW management principles and improving environmental standards.

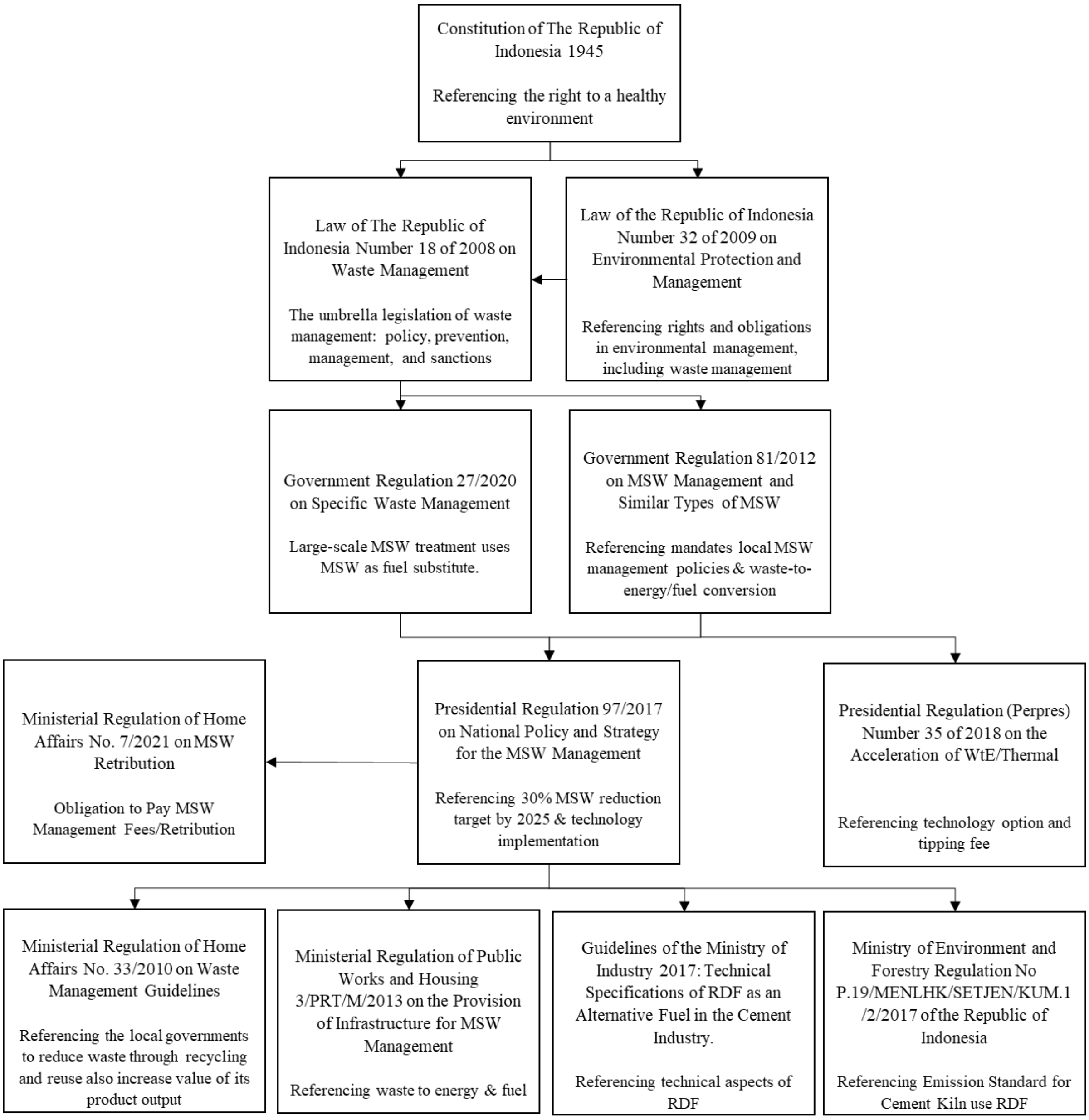

Figure 3. 4 Summary of Regulations Related to MSW conversion Into RDF in Indonesia (adopted; BPKRI, 2024)

Indonesia's waste management regulations are specifically governed by the Law of the Republic of Indonesia Number 18 of 2008 on Waste Management. Compared to Europe, it falls under the umbrella of Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018, which amends Directive 2008/98/EC on waste (EP, 2018). This directive is a principal document and provides the framework for all subsequent detailed legislation. It is also the basis for the prohibition of landfilling.

For Indonesia, future synergies are expected with regulations concerning EPR and carbon trading as an incentive for applying MSW management regulation, which is currently facing implementation barriers. Additionally, regulations will accelerate the adoption of WtE and RDF as part of MSW management.

3.2 Overview of MSW Management in Jabodebek

Jabodebek (Jakarta City, Bogor Regency, Depok City, and Bekasi City) constitute an economic zone with Jakarta as the capital city and the surrounding areas serving as satellite cities. Socially, residents exhibit a consumerist culture and commute between cities, resulting in similar conditions (Sadewo, 2018). To better understand the conditions in Jabodebek, Table 3.1 provides data on the population and waste generation.

Table 3. 1 Population and Waste Generation in the Region

Parameter	Unit	Jakarta[1]	Bogor[2]	Depok[3]	Bekasi[4]	Jabodebek	Indonesia[5]
Population	million	10.7	5.5	2.1	2.5	20.8	281.5
Population Density	people/km^2	16,145	1,835	10,711	11,583	5,110	147
MSW	Mg/day	8527	2688	1400	1830	14,445	188,886
MSW	Mio. Mg/year	3.1	1.0	0.5	0.7	5	68.9
Area	km^2	662	2,992	200	213	4,067	1,919,440

([1]BPS Bekasi, 2022; [2]BPS Bogor Regency, 2022; [3]BPS Depok, 2022; [4]BPS Jakarta, 2023; [5]KLHK, 2023)

Based on the data above, Jakarta has the largest population and MSW generation. In comparison to the entire area of Indonesia, the Jabodebek region covers only about 0.21% of the total land area. However, it contributes around 7% of the country's population and generates approximately 8% of the MSW in Indonesia. Additionally, the population density in Jabodebek is far greater than the national average. Therefore, addressing MSW-related challenges in this region would considerably impact Indonesia's overall situation.

In the implementation of MSW management and its regulations, the region generally aligns with the process depicted in Figure 3.3 and follows the hierarchical order of regulations outlined in Figure 3.5. However, one prominent issue faced by the cities in this region is landfill overcapacity due to about 90% of the MSW management relying on landfill (Suryani, 2022). Several local regulations pertaining to MSW management have been established, as shown in Table 3.2 on the following page.

Table 3. 2 MSW Legislations in the Jabodebek

City	Regulation	Key Points
Jakarta	Provincial Regulation No.4 of 2019, MSW Management	Rights, obligations and sanctions, landfill restrictions, 3R, self-management of MSW for industrial and commercial areas, WtE and RDF production
	Governor Regulation No. 46 of 2023, MSW Management Tariff	Tariff for waste transportation services, landfill fees, pricing of RDF and recycled materials.
Bogor	Regency Regulation No. 88 of 2018 on the policy and strategy of Bogor Regency in MSW Management	Rights, obligations and sanctions, 3R, landfill restrictions, tariff of services, and implementation of technology in waste management
Depok	Local Regulation of the Depok City No. 13 of 2018 on Waste Management	
Bekasi	Local Regulation No. 2 of 2021 on Waste Management	

Source: (BPKRI, 2024)

Subsequently, the status of landfills in this region is presented, where they remain the predominant method of MSW management, as illustrated in Table 3.3.

Table 3. 3 Landfill in the Regions

Region	Landfill Location	Area (ha)	Average Height of Landfill (m)	Start of operation year	Situation
Jakarta[1]	Bantargebang	110.3	40-50	1989	The landfill uses a sanitary system with a solid cover and membrane, has reached overcapacity, features a structured zoning system divided into five zones, and has many informal waste pickers sorting through the waste at the landfill.
Bogor[2]	Galuga	31.8	20-40	1996	The landfill was designed to use a sanitary system with a solid cover and membrane. However, in practice, this has not been applied due to overcapacity and limited operational expenditure, leading to numerous informal waste pickers sorting through the waste piles at the landfill.
Depok[2]	Cipayung	10.6	30-40	1984	
Bekasi[2]	Sumur Batu	22.0	20-40	2001	

Source: ([1]DLH Jakarta, 2023; [2]KLHK, 2023)

Among the cities in the region, Jakarta has been the most rapid in implementing technology adoption regulations. This is mainly due to the initial support from the central government, given Jakarta's status as the capital city. Jakarta began its efforts by constructing WtE and RDF plants at the Bantargebang landfill, showcasing its commitment to sustainable waste management practices and reducing environmental impacts. These initiatives demonstrate the city's proactive approach and pave the way for other cities in the region to implement the technological approach of MSW management, as depicted in Figure 3.5 on the following page.

Figure 3. 5 WtE (left) and RDF Production in Jakarta (right)
(DLH Jakarta, 2023)

The WtE facility that was constructed in Jakarta commenced operations in 2019. It utilises MSW as fuel, with a capacity of 100 Mg per day for approximately 200-300 operational days per year, producing electricity amounting to 700 kW (DLH Jakarta, 2023). However, the WtE facility is currently running at less optimal efficiency, highlighting the need for significant operational expenditures. As a result, Jakarta initiated an RDF production plant project the following year, beginning in 2021. The initial capacity of this project was 50-70 Mg per day, which has since been planned to handle 2,000 Mg of MSW per day, as projected in 2025. The RDF production plant is currently undergoing development and has already secured contracts with two cement factories in Bogor to serve as RDF suppliers. This strategic collaboration is facilitated by the proximity of the two cement factories to Jakarta, with both locations situated within a distance of less than 50 km. If the RDF production plant proves successful, it would significantly ease the process of persuading other regional city governments to replicate it, establishing it as a roadmap for MSW management in the future.

4. The Cement Plant Overview

4.1 Energy Demand and Sources

The cement plant referred to in this study is a cement plant owned by Indocement, a leading cement company in Indonesia. located in Citeureup, West Java. With an annual installed capacity of 16.3 million Mg, the cement plant needed about 24,800 TJ of energy for its production process in 2023. Of this energy demand, 18.3% was sourced from alternative fuels (AFs), while coal accounted for the remainder (Indocement, 2024). Meanwhile, another cement brand in Indonesia, in 2023, utilised an AF range from 0.3-19% (ASI, 2023). The cement industry utilises various types of waste and materials as AFs. These include solid waste such as agricultural and non-agricultural biomass, oil-based waste, and mixed and hazardous waste. Each type of AF has different energy values. For example, used tyres have an energy value of 23.03 MJ/kg, while rice husks have an energy value of 19.93 MJ/kg (Beguedou et al., 2023). The use of AF helps reduce dependence on conventional fossil fuels and provides environmental and economic benefits to the cement industry. In 2023, the total AF utilised amounted to approximately 348 Tg, which is estimated to have reduced coal consumption by 240 Tg, while the coal used was about 952 Tg.

The cement plant uses fuels like coal, oil, and gas, along with alternative sources such as biomass and industrial waste, mainly from local Indonesian sources to reduce costs. RDF is sourced nearby for logistical efficiency. Figure 4.1 below displays the various fuel sources.

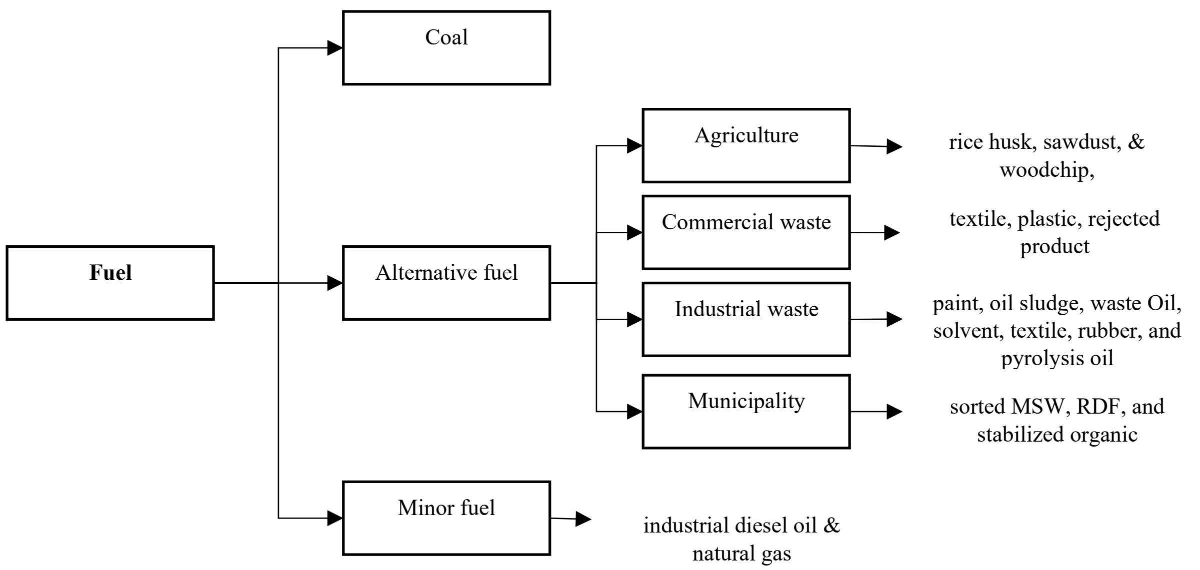

Figure 4. 1 Fuel Sources in the Cement Plant
(Indocement, 2024)

The energy needs of the cement plant are closely tied to the fluctuating market demand for cement products. As the construction sector and housing demands expand, the plant's energy consumption increases, necessitating a sustainable approach to energy sourcing. This has led to a gradual shift towards AFs. This transition is impacted by a mix of elements, comprising strict legal mandates aimed at reducing emissions, a market preference for environmentally friendly production practices, and technological advancements that improve the effectiveness of AF. These components are propelling the cement industry towards a greener tomorrow, with continuous progress anticipated to continue shaping the energy approaches of cement factories (Anwar, 2022).

4.2 Fact & Figure of Indocement

This study highlights the ambition of Indocement, a prominent cement company in Indonesia, to utilise RDF as a sustainable material in line with their corporate purpose of "Material to Build Our Future". The company ranks second in Indonesia's cement industry's market share in 2023, approximately 25-30% of the market share (ASI, 2023). The company is a leading private supplier of cement, concrete, aggregates, and mortar in Indonesia, consistently chosen as the top brand by consumers, winning the Top Brand award 15 times, most recently in 2023 (Frontier, 2023). Founded in 1975 with a capacity of 500,000 Mg in Citeureup, the company now operates five plants across Indonesia, boasting a combined annual production capacity of approximately 29 million Mg as of 2023. Figure 4.2 depicts the locations of the company's plants.

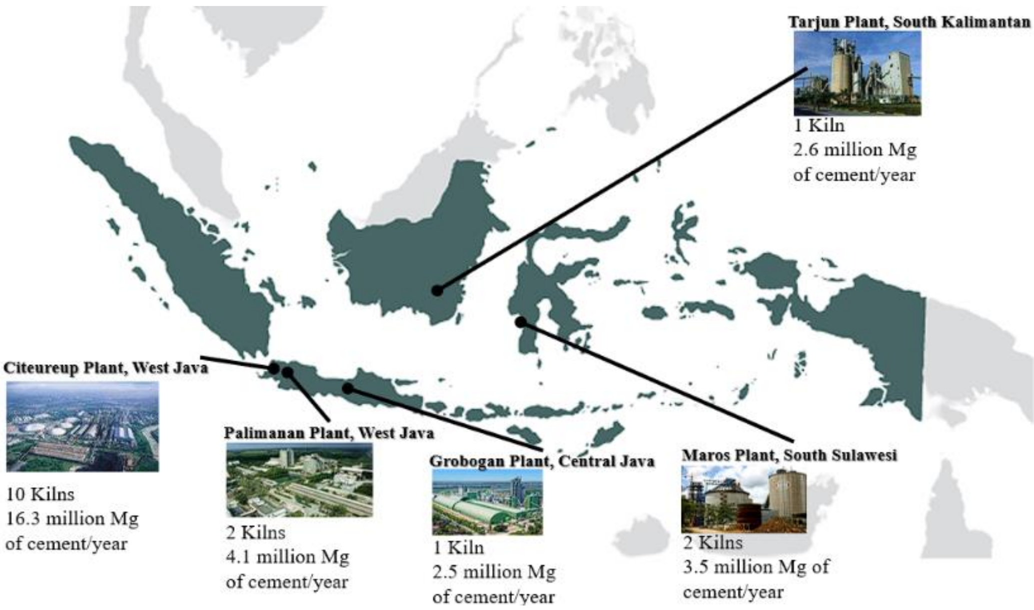

Figure 4. 2 Map of Indonesia and Plant Sites Location of Indocement
(Indocement, 2024)

The investigation in this study focuses on the company's cement factory at the Citeureup Plant, West Java. It will be referred to as the cement plant in subsequent references. The cement plant has 10 Kilns with a capacity of up to 16.3 million Mg annually. The cement plant covers an area of approximately 300 hectares, including its supporting facilities and a quarry area of around 5,200 hectares. Since 2005, the cement plant has been utilising AFs, starting with biomass and then expanding to hazardous waste, commercial and industrial waste, and RDF from MSW. In the context of cement plants, using RDF as an AF source can aid in diminishing greenhouse gas emissions and MSW while reducing dependency on fossil fuels.

The utilisation of RDF is expected to enhance cost efficiency in cement production by reducing fuel costs. The cement plant has 7 kilns capable of utilising AFs. These kilns, namely Kiln 3, Kiln 4, Kiln 6, Kiln 7, Kiln 8, Kiln 11, and Kiln 14, contribute to reducing fuel expenses. Furthermore, the cement plant is equipped with an AF treatment facility that ensures the proper handling and utilisation of RDF. RDF also plays a vital role in optimising fuel efficiency and cost-effectiveness (Mujayyin et al., 2020).

The plant also houses a reliable and certified Laboratory to maintain quality standards. This Laboratory conducts comprehensive tests and analyses to ensure adherence to specifications and regulations throughout the production process. Additionally, the cement plant implements continuous emission control and monitoring systems, which comply with current regulations. These systems effectively monitor and control emissions to minimise environmental impact and ensure compliance with environmental standards.

4.3 Strategy of Indocement for Sustainability & CO_2 Reduction

Using AFs at the cement plant is a key component of the Indocement's commitment to sustainability and the reduction of CO_2 emissions. This approach is deeply rooted in the company's core principle of resource management. By focusing on eco-efficiency, the company aims to enhance how energy and material resources are utilised, ensuring that production processes are as environmentally friendly as possible. Additionally, the company is dedicated to the principles of industrial ecology, which involves the recovery and innovative reuse of waste and by-products from various industries, transforming what was once considered waste into valuable resources.

Supporting the development of a circular economy is also a pivotal aspect of the Indocement's strategy. Indocement not only minimises its environmental impact but also fosters economic growth that is both sustainable and regenerative. The company actively encourages and creates opportunities for other entities and governments to become partners in AF supply, thereby promoting a synergistic relationship that reduces the potential for waste and enhances its sales value. This collaborative effort is instrumental in building a more sustainable industry and a healthier planet. In response to the aforementioned initiatives, the company has devised a roadmap focusing on two crucial elements: the implementation of AFs and the objective of minimising CO_2 emissions (Mota & Kim, 2019). Figure 4.3 depicts the roadmap of Indocement to utilise AFs and reduce CO_2 emissions.

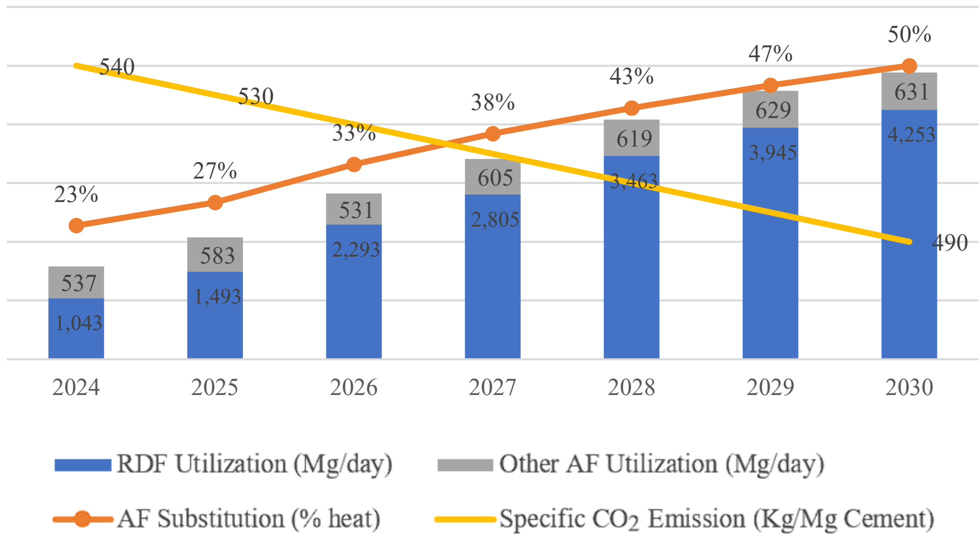

Figure 4. 3 Indocement's AF Utilisation and CO_2 Emission Reduction Target (Indocement, 2024)

To enhance this strategy further, the company plans to incrementally increase the AF feeding capacity at the cement plant. The target for 2023 is set at approximately 1,000 Mg per day, with an anticipated growth of 2,000 Mg per day by 2025 and a substantial rise to 4,800 Mg per day or up to 50% of the substitution rate by 2030. The use of AF will directly impact reducing specific CO_2 emissions. This ambitious expansion necessitates a comprehensive evaluation of the potential availability of AF and securing RDF sources as a crucial preliminary step. Securing these RDF sources is essential before investing in increasing the AF feeding capacity. Consequently, this study is vital in ensuring a stable RDF supply for the future, underpinning the company's long-term sustainability goals. The company has established RDF specifications for the cement plant as part of its policies. Table 4.1 outlines these specifications.

Table 4. 1 RDF Specification in The Cement Plant

Quality Parameter	Unit	Spec 1	Spec 2	Spec 3	Spec 4	Spec 5
Particle Size						
• Preference	mm, 2d	≤50 x 80	≤50 x 80	≤50 x 80	≤50 x 80	≤50 x 80
• Tends to be limited	mm, 2d, 3d	≤150 x 150	≤150 x 150	≤150 x 150	≤150 x 150	≤150 x 150
• Limited use only	mm, 2d	≤300 x 300	≤300 x 300	≤300 x 300	≤300 x 300	≤300 x 300
MC	%wt. (ar.)	≤20	≤20	≤20	≤35	≤45
HHV	MJ/kg	≥25	≥19	≥15	≥10	≥6
Sulfur	%wt. (db.)	≤0.1	≤0.1	≤0.2	≤0.4	≤0.6
Chlorine	%wt. (db.)	≤0.2	≤0.6	≤0.75	≤0.75	≤1.25

(Indocement, 2024)

5. Methodology and Research Program

This section will explore the methodology utilised in this research, providing the structural foundation for the conducted investigation. Figure 5.1 illustrates the process flow of the research concept that has been applied.

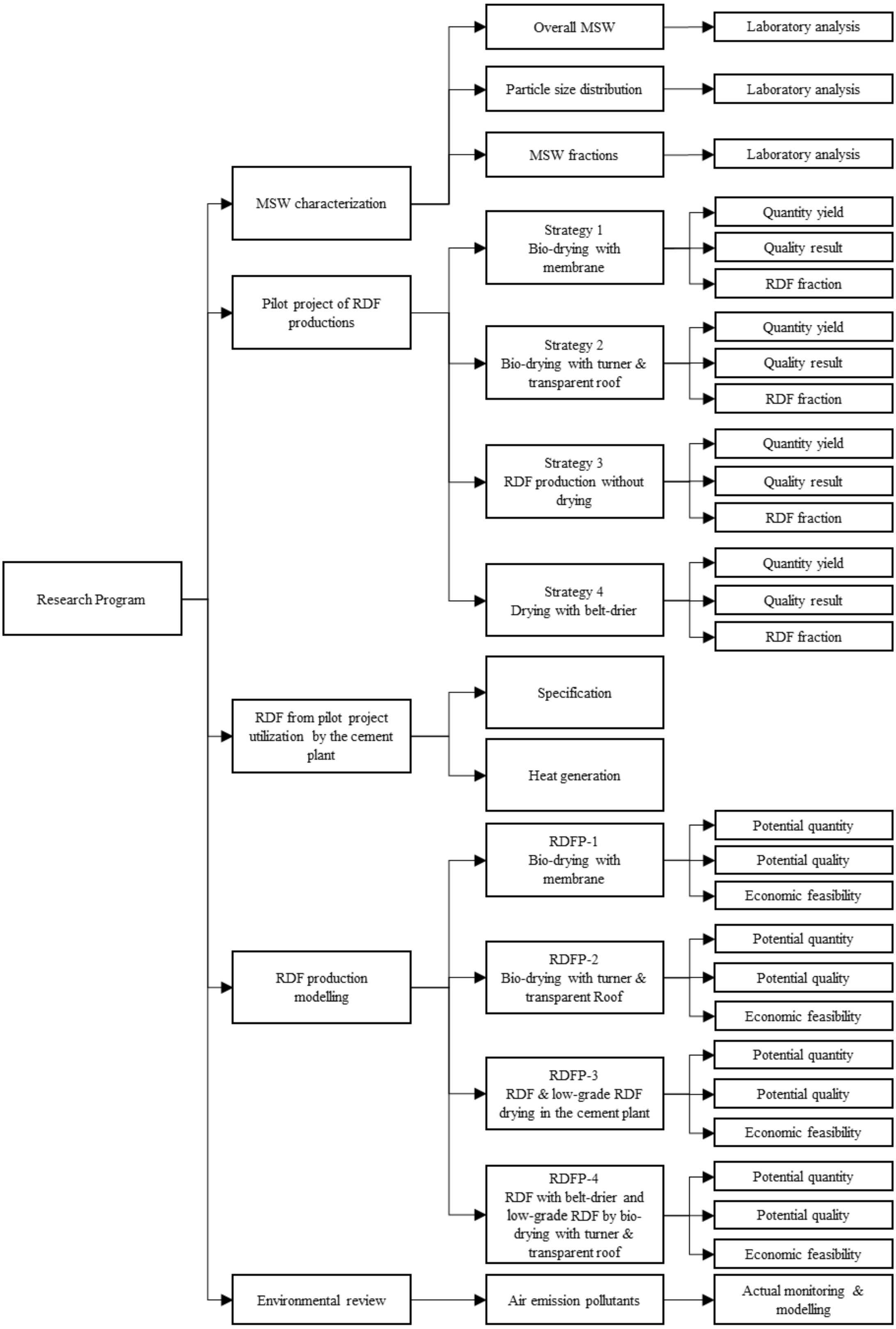

Figure 5. 1 Flow of the Research Program

5.1 Scope of the Investigation

This research focuses on four regions near the Citeureup, Bogor Regency cement plant, which are less than 50 km from the MSW source. The study focuses on the potential of RDF in the selected regions of Jakarta, Bogor regency, Depok, and Bekasi (Jabodebek). Figure 5.2 displays the sites of the MSW origins and the cement plant.

Figure 5. 2 Location of the MSW Sources and the Cement Plant.

The samples of MSW were not collected directly from households but rather from local intermediate MSW storage facilities located in these four cities. This approach was implemented to facilitate the sampling process and ensure ease of collection. The approach represents a best practice in gathering MSW as a source for RDF production. In these storage facilities, the MSW usually accumulates for a few days and undergoes a manual sorting process. During this process, items that hold commercial value or are recyclable, such as paper, plastic, and metal, are commonly taken by waste pickers for resale purposes (Mastufatul et al., 2023). Subsequently, the MSW samples were transported to the cement plant using trucks with a 6-8 m3 capacity, with an average carrying capacity of 2-3 Mg per truck. These samples were analysed at the cement plant's facility, which co-exists with an AF treatment facility. Figure 5.3 presents an example of the MSW sampling source.

Figure 5. 3 Intermediate Collection Centres as MSW Source and MSW Truck

Table 5.1 MSW Sampling Collection

No	Urban Area	Unit	Jakarta City[5]	Bogor Regency[3]	Depok City[4]	Bekasi City[2]	Total
1	Sample collection duration	days	8	8	8	8	
2	Trucks sample count in summer	unit	56	56	56	56	224
3	Trucks sample count in rainy	unit	56	56	56	56	224
4	Total trucks sample count	unit	112	112	112	112	448
5	Samples taken per truck	Mg	2.84	2.79	2.78	2.88	2.82
6	Total samples taken	Mg	318	313	312	323	1,265
7	Daily MSW generation	Mg/day	8527[4]	2688[2]	1400[3]	1830[1]	14,445
8	Sampling schedule in summer		8-15 May 2023	22-29 May 2023	5-12 Jun 2023	19-26 Jun 2023	
9	Sampling schedule in rainy		12-19 Dec 2022	9-16 Jan 2023	28 Nov - 5 Dec 2022	23-30 Jan 2023	
10	Rainfall in summer		50-100 mm/month[1]				
11	Rainfall in rainy		250-400 mm/month[1]				

([1]BMKG, 2023; [2]BPS Bekasi, 2022; 3BPS Bogor Regency, 2022; [4]BPS Depok, 2022; [5]BPS Jakarta, 2023)

Table 5.1 indicates that the sampling was carried out during both the rainy and summer seasons, which encompass variations in weather conditions that may affect the sample characteristics. Seasonal differences can influence the sample examination results (Ibikunle et al., 2020). A total of 448 truckloads of samples were obtained across all four cities. Utilising a significant number of truckloads facilitated the selection of representative samples from each city under investigation. The sampling of MSW was conducted using random sampling for eight consecutive days for RDF production. This will be validated through data consistency testing using mean and standard deviation, as recommended to obtain comprehensive samples by the standard MSW sampling method (BSNRI, 1994). The subsequent figure 5.4, illustrates the procedure for collecting and distributing the samples.

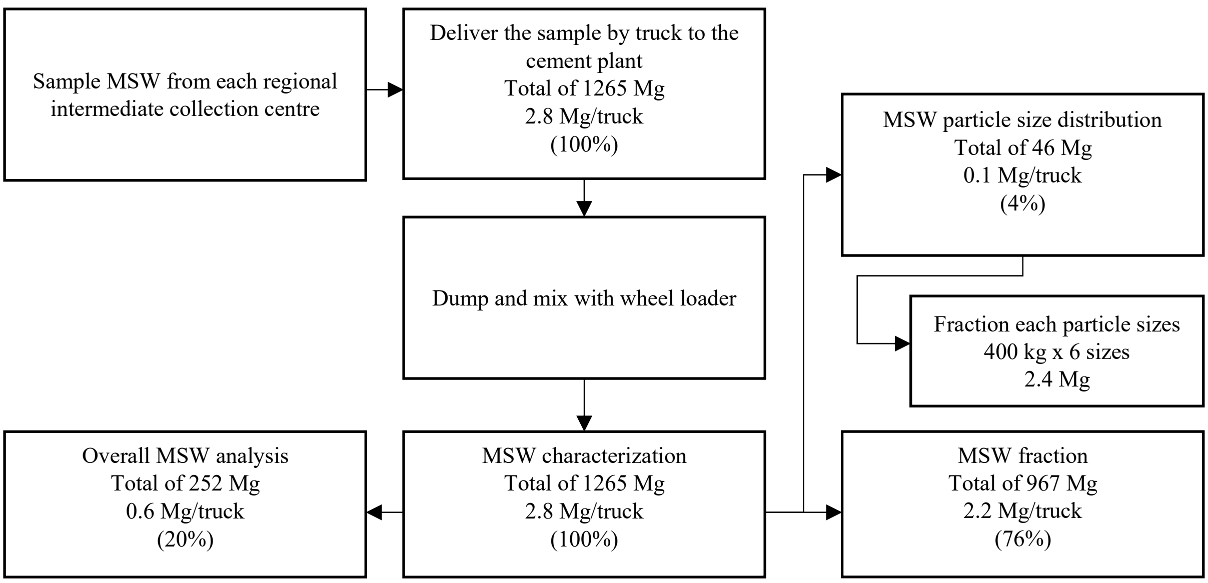

Figure 5. 4 MSW Samples Distribution

Upon arrival, samples from each truck are thoroughly mixed to ensure enhanced homogeneity. Next, the samples were spread out as seen in Figure 5.4. As stated in Wirosoedarmo et al. (2021), mixed MSW samples can become homogeneous through thorough mixing processes. With the appropriate mixing techniques, samples can achieve the required level of homogeneity for analysis or testing. However, it is essential to consider the unique characteristics of the MSW to achieve optimal results. The total sample for MSW fraction analysis consists of the remaining samples after a portion has been allocated for the overall MSW and particle size distribution analysis. Thus, based on the conducted sample collection, this research is expected to provide a comprehensive understanding of the characteristics of MSW samples in the four urban areas, serving as a reference for further analysis.

5.2 Investigation Program

The research program delineated within this study is segmented into three distinct phases: initially, the characterisation of MSW, the pilot project of the RDF production and the utilisation of RDF produced by the cement plant. The findings derived from these tripartite components will lay the groundwork for formulating an RDF production model, which will be discussed in another research section.

The sampling process entailed gathering representative MSW from each city for characterisation analysis. These samples were then distributed for three distinct analyses, namely overall analysis, particle size distribution analysis, and fractions analysis. The overall MSW analysis sampling method was utilised to collect random samples that adequately represent the overall composition of MSW from each city, providing a general analysis of the quality of MSW (Rania et al., 2019). Furthermore, the particle size distribution is very important in considering the performance of mechanical treatment and plays a crucial role in developing efficient strategies for processing and managing MSW (Zhang et al., 2019). Conversely, MSW fractions analysis were conducted to determine the composition of different MSW fractions, including organic waste, plastics, paper, and others. This analysis offered valuable insights into the potential composition of MSW fractions and size, serving as a foundation for treatment modelling based on the fraction composition of MSW (Putri et al., 2022). This resonates with Mascarenhas et al. (2021) findings, where the analysis of MSW samples was deemed crucial in making informed decisions regarding the processing of MSW. The initial phase of the research program involves the characterisation of MSW, starting with the first step of overall sampling analysis. The samples are taken from 4-5 different points, amounting to an estimated 500-600 kg from the truck. Figure 5.5 illustrates the process of sample collection.

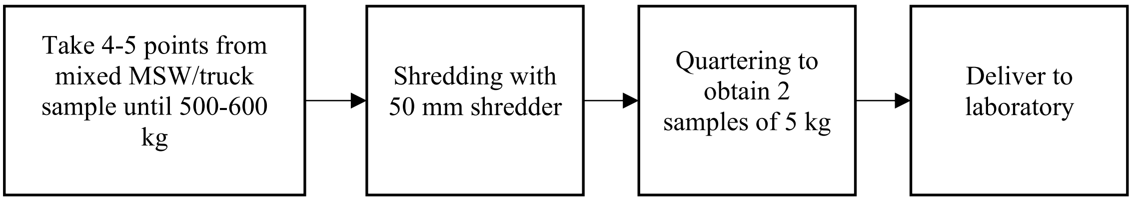

Figure 5. 5 Overall MSW Analysis Sampling

The total number of samples collected amounts to 252 Mg, with an average of 560 kg per truck. These samples were shredded to 50 mm and subjected to the quartering process to prepare them for Laboratory examination. The second step of MSW characterisation concentrates on analysing the range of particle sizes in MSW. This step is crucial for understanding the size composition of the MSW material. A sizable sample weighing roughly 100 kilograms was carefully chosen from the mixed MSW pile. This representative sample was then used specifically to evaluate the particle size distribution within the MSW. Figure 5.6 illustrates the process of distributing particles by size.

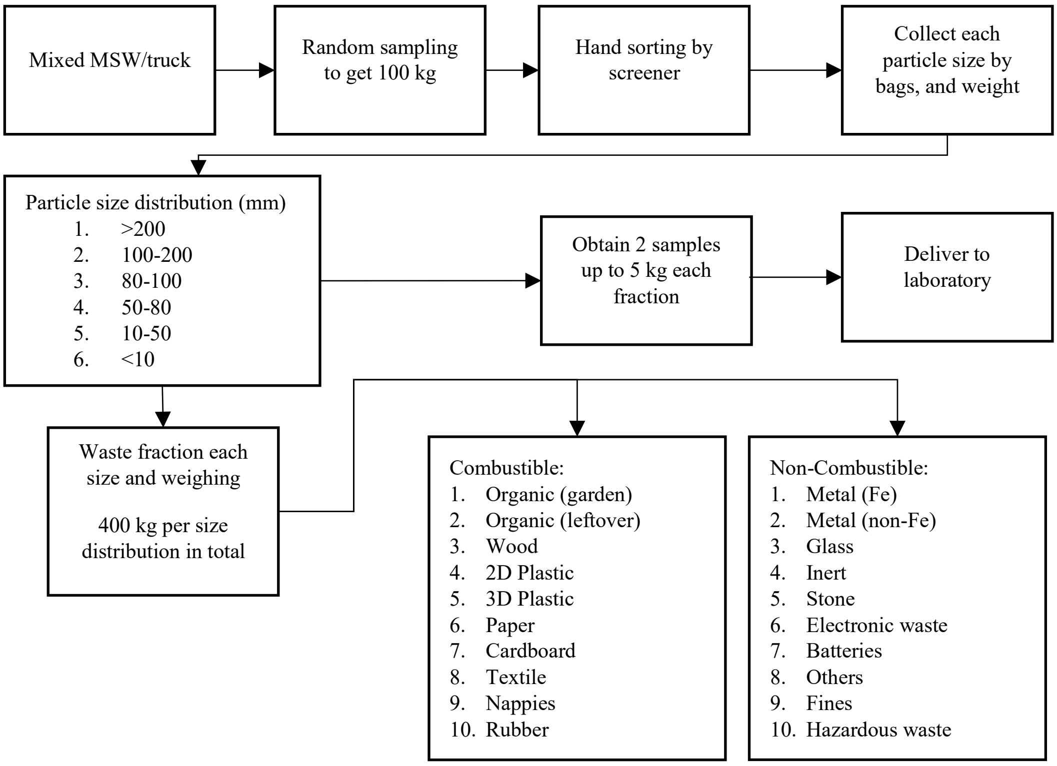

Figure 5. 6 Particle Size Distribution Procedure

In-depth particle size analysis, encompassing a spectrum of size ranges from >200 mm, 100-200 mm, 80-100 mm, 50-80 mm, 10-50 mm, to <10 mm, is indispensable for an exhaustive understanding of the intrinsic MSW composition. Such granular scrutiny divulges the variegated nature of the MSW and is instrumental in tailoring the treatment process to enhance RDF quality. Figure 5.7 provides an example of the sampling process for particle size distribution.

Figure 5. 7 Example of Particle Size Distribution Analysis Processes

The concluding step of MSW characterisation focuses on the MSW fraction, with these samples constituting a significant portion (76%) of the aggregate samples. These specimens were primarily residual from the prior phase of the project. This thorough approach was taken to ensure that the results accurately reflect the composition of the MSW. Figure 5.8 depicts the analysis procedure of MSW fractions.

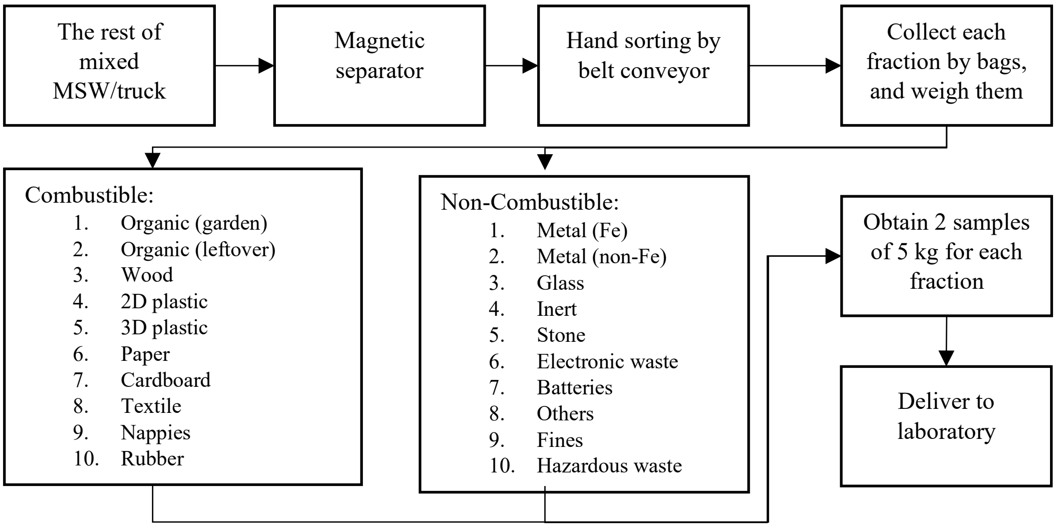

Figure 5. 8 MSW Fractions Analysis Procedure

MSW fractions, can be divided into two main categories: combustible and non-combustible. The combustible fraction consists of materials that can be burned, such as organic waste like food leftovers and garden waste, wood, plastics (both 2D and 3D), paper, cardboard, textiles, diapers, and rubber. Additionally, the characterisation of a 77 Mg MSW sample from Jakarta has been conducted to reveal the PVC fraction, which is vital for RDF production and ensuring environmental compliance in cement kiln utilisation. PVC poses fire risks as a precursor to toxic substances like dioxins and complicates waste management due to chlorine and toxic additives. PVC is also unsustainable due to problematic additives, difficult recycling, and mercury emissions from chlor-alkali electrolysis, prompting cities in Germany and other countries to ban its use in public construction projects (Lahl & Lahl, 2024). On the other hand, the non-combustible fraction consists of materials that are not easily burned, such as metals (both iron and non-iron), glass, stone, electronic waste, batteries, and other hazardous materials. This classification aids in MSW management, as combustible materials can often be recycled or used as AF, while non-combustible materials usually require different processing (Alfè et al., 2022). Evaluating MSW fractions is essential for RDF production. The mix of materials like plastic and paper is key to RDF's process and quality. Their calorific value affects RDF's energy potential. Analysing these fractions helps create an RDF mix with optimal energy content, as measured by the LHV.

The LHV is crucial for RDF quality. The composition of MSW fractions, especially the presence and ratio of materials, impacts RDF's LHV. More plastics can raise the LHV due to their higher calorific value, while paper's impact varies depending on its type and condition. Systematic MSW analysis ensures RDF meets the energy needs for uses like cement kilns, where high energy content is vital (Zhao et al., 2016). Figure 5.9 presents the hand-sorting method used in the fraction analysis.

Figure 5. 9 Belt Conveyor for Hand-Sorting and Samples for Laboratory Analysis

Figure 5.9 also shows MSW fractions that have been separated through hand-sorting (the figure on the right side). These separated MSW fractions were transported to the laboratory, where a thorough analysis would be carried out. Upon sorting, these MSW fractions were transformed into pivotal informational pieces, establishing a cornerstone for the multifaceted experiments foundational to the overarching research process.

Table 5.2 enumerates examples of materials associated with each distinct fraction, akin to a reference guide for the MSW fractions analysis process. This organized enumeration of materials is expected to facilitate the identification of various MSW components during the investigative phase of the research. The assortment of MSW types listed represents the heterogeneity the study seeks to dissect, with each specific material contributing to the broader understanding of MSW fractions composition.

Table 5. 2 Material Examples for Each MSW Fraction

No	MSW Fraction	Material Examples
A	**Combustible**	
1	Organic (garden)[1]	Branches, leaves, grass, and plants cuttings
2	Organic (leftover)[1]	Food waste, leftover meat cuts, vegetables & fruits, and beverage residues such as coffee & tea
3	Wood[1]	Remnants of wooden boxes, wooden pallets, and bamboo
4	2D Plastic[1]	Flexible packaging, multi-layer, sachet, plastic bags, and sacks
5	3D Plastic[1]	Bottled, boxed packaging, toys, bucket, and leftover household furniture
6	Plastic PVC[1]	Plumbing pipes, clear food packaging, and toys
7	Paper[1]	Magazines, leaflet-brochures, documents, books, and packaging materials.
8	Cardboard[1]	Carton, packaging cardboard, and food packaging cardboard
9	Textile[1]	Rags, used clothing, banner, accessories, packaging, and leftover fabric from household furniture
10	Nappies[1,3]	Diapers, sanitary pads, and bandage
11	Rubber[1]	Rubber band, scrap tyres, gloves, and hose/tubing
B	**Non-Combustible**	
1	Metal (Fe)[1]	Eating utensils, small metal pieces or fragments, nail, screw, nut, and broken tools
2	Metal (non-Fe)[3]	Aluminium can, food wrap, bottle caps. and aluminium foil
3	Glass[1]	Drink bottles, medicine bottles, cooking ingredient bottles and glass-plates or dishes
4	Inert[1]	Concrete fragments, porcelain fragments, and bricks
5	Stone[1]	Small rocks and gravels
6	Electronic waste[2]	Handphone and PCB
7	Batteries[2]	Batteries, rechargeable battery, and watch battery
8	Others[1]	Mixed solid material and unspecified material
9	Fines[3]	Residue < 10mm
10	Hazardous waste[2]	Lamp, hardened paint, car battery and printer cartridge

([1]EIB, 2024; [2]KLHK, 2023; [3]Shu et al., 2023)

In the Table 5.2 above, the term "combustible fraction" refers to materials that can be burned, such as organic matter, wood, plastic, paper/cardboard, textiles (including nappies), and rubber. Within the combustible fractions, there is a biomass category, which consists of organics, wood, and paper/cardboard (Moreno et al., 2019).In contrast, the rest of the materials that are not easily combustible are called non-combustible (Phelps et al., 1995).

In the research's second phase, a pilot project was carried out to process MSW for the production of RDF. For each trial, conducted eight to ten times, approximately 100 Mg of MSW were used and transported to the pilot plant location owned by the cement plant. The objective was to assess the effectiveness of the treatment methods in RDF production. Figure 5.10 delineates the four strategies implemented during this phase.

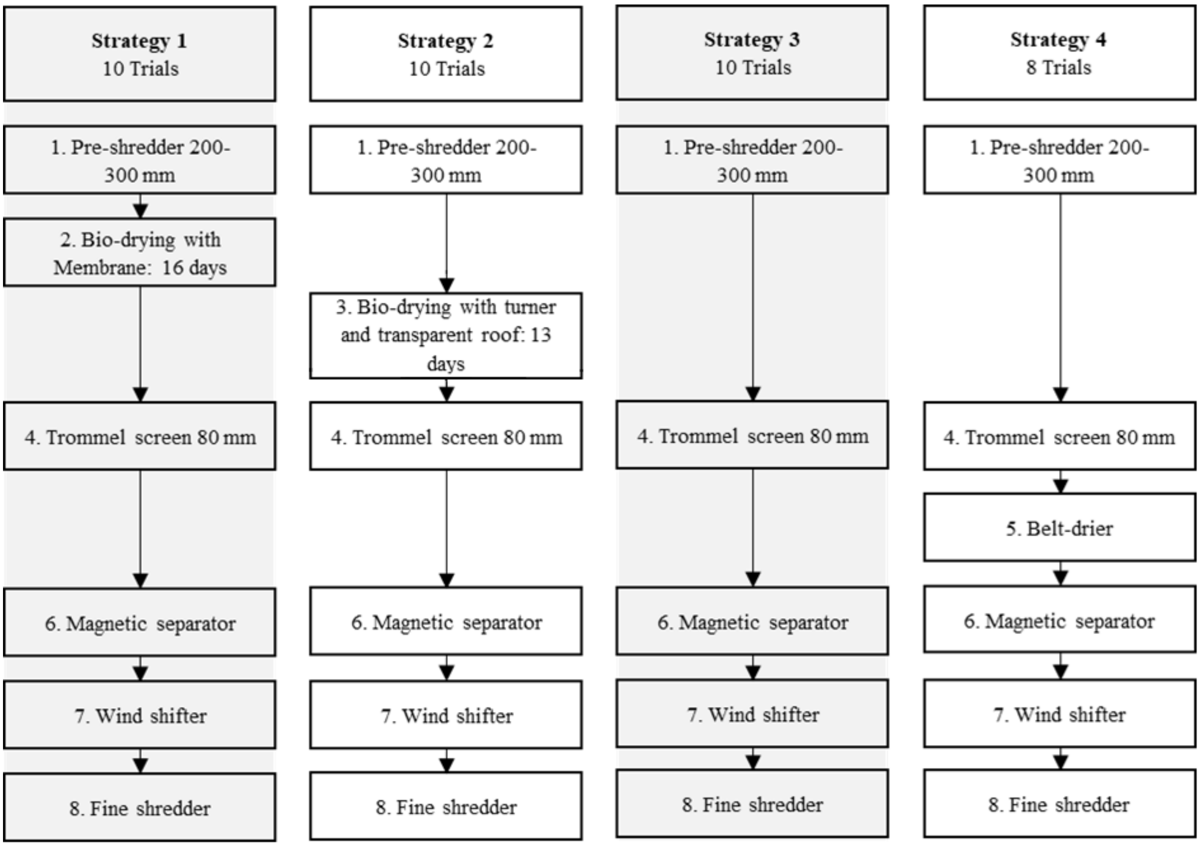

Figure 5. 10 Pilot Project Strategies

The main difference between the four strategies lies in their MSW drying methods. Strategy 1 employed bio-drying with a membrane, while strategy 2 utilised bio-drying with a turner and a transparent roof to facilitate drying through sunlight-solar exposure. Strategy 3 had no drying process and relied solely on mechanical treatment. Lastly, strategy 4 employed thermal drying with a belt drier prototype.

Furthermore, the key equipment employed in the four pilot project strategies is explained. It includes detailed accounts of these machines' functions and roles in the MSW treatment process. Understanding the equipment's capabilities is instrumental in assessing and comparing the performance and efficiency of the various strategies.

The first piece of equipment is the pre-shredder, as shown in Figure 5.10, marked with number 1. The pre-shredder was employed across all strategies in the pilot project. This device efficiently cuts and tears waste material down to a smaller, more uniform size, thereby enhancing the subsequent stages of treatment (Oladejo et al., 2020).

Figure 5. 11 Pre-shredder

Figure 5.11 above depicts a pre-shredder with a processing capacity of 5-10 Mg per hour, producing output material reduced to 200-300 mm sizes. The throughput and the dimensions of the material produced by this device are essential to maintain the smooth progression of subsequent processes. Should a bottleneck occur at this juncture, it would present significant impediments to the efficiency of the following stages.

The next equipment is bio-drying with membrane (equipment no. 2), which was only implemented in strategy 1. This process is crucial as bio-drying has been proven effective in reducing the moisture content of MSW by optimising environmental conditions such as temperature, moisture content, turning with wheel loader and aeration, microbial activity is enhanced, leading to the evaporation of water (Ham et al., 2019). Figure 5.12 illustrates the bio-drying with membrane procedure.

Figure 5. 12 Bio-drying with Membrane Procedure

In the facility used in this pilot project, there are 2 bays with a capacity of 100 Mg each, totalling 200 Mg. Each bay has dimensions of 7.5 x 40.0 m with a wall height of 1.2 m and an MSW stack height of up to 2.7 m. The facility has blowers and aeration pipes. Agitation is performed using a wheel loader every five days. Additionally, a portable temperature probe is provided. The bio-drying process in this pilot project took 16 days per batch. The moisture target was about 30% in the output product.

The next is equipment no.3, exclusively applied in strategy 2. It is equipped with a turner machine, and the process conducted in a warehouse with a transparent roof to facilitate drying with the assistance of sunlight. As illustrated in Figure 5.10, this equipment is labelled as number 3. With the aid of solar heat, the bio-drying process can accelerate the evaporation of moisture contained in MSW and achieve a moisture content of less than 20% (Ngamket et al., 2020). In principle, equipment no. 2 and 3 operates using the same bio-drying approach. This refers to a process that harnesses heat generated from microbial activity. As long as there is a sufficient level of organic fraction, it is recommended to have at least 30% organic content (Ma et al., 2021). The layout of the facility is illustrated in Figure 5.13 below.

Figure 5. 13 Bio-drying with Turner

The pilot project of strategy 2 was conducted in a warehouse without using bays and active aeration, unlike strategy 1. The MSW piles were created according to the size of the turning machine, with an optimal stack height of 2.3 m and width of 4.5 m. Therefore, to accommodate 100 Mg of MSW, a stack length of 65 m is required. Turning the MSW was performed twice a day, in the morning around 9-10 am and the afternoon around 3-4 pm. Additionally, this strategy was supplemented by a solar drying process which could expedite the drying phase (Noori et al., 2022). The bio-drying process in this pilot project took 13 days per batch. The moisture target was about 30% in the output product.

Equipment no. 4 used in the study is a trommel, utilised in all four strategies (Figure 5.10). The trommel, a rotating mechanical device, separates MSW particles into two categories based on their size: those that are larger than 80 mm and those smaller than 80 mm. This separation is expected to enhance the quality of the resulting RDF by segregating materials with a low heating value that falls below the 80 mm limit. This aligns with Zhu et al., (2009) findings, where the trommel screen plays a crucial role in sorting MSW by segregating particles based on their size and separating the organic fraction from others, such as paper and plastic. Figure 5.14 below presents the trommel screen that was utilised.

Figure 5. 14 Trommel Screen 80 mm

The trommel features an 80 mm opening and a sieve area of 70-80 m², with dimensions of 12 m in length and 2.5 m in diameter. It rotates at 12 rpm and processes up to 10 Mg/hour. The 80 mm particle size selection prevents excessively coarse or fine particles, optimising for materials larger than 80 mm, which have better calorific value and lower ash content (Malaťák et al., 2018). In addition, materials with $\leq$80 mm size are still within the optimal combustion size at the cement plant.

The next piece of equipment is the belt dryer, labelled as no. 5 (see Figure 5.10). This belt dryer is one of the thermal treatment methods for MSW, utilising heat from electricity or other sources. It is commonly used for MSW drying. According to Tun & Juchelková (2019), drying MSW using thermal energy can achieve rapid and significant drying. Figure 5.15 below shows the belt dryer employed in this pilot project.

Figure 5. 15 Belt Drier

The belt dryer in this study is still a prototype with a maximum capacity of 3-4 Mg/hour and is equipped with two blowers, each with a power of 11 kW and a maximum air-blowing capacity of 22 m^3/min. The total heater power is 288 kW, allowing it to reach a working temperature of up to 270°C. The dimensions of this equipment are 14 m in length with a belt width of 2 m. It has a 5 mm opening of the metal belt.

In this pilot project, the sixth equipment utilised is a magnetic separator installed above the belt conveyor. According to the research conducted by Back et al., (2020), magnetic separators are commonly employed to separate ferrous metals from MSW processing. This equipment separates ferrous metals from MSW materials using the principle of magnetic force. Figure 5.16 illustrates the magnetic separation equipment utilised in the study.

Figure 5. 16 Magnetic Separator

Equipment no.7 used is wind-shifter (see Figure 5.10) As Sengupta et al., (2022) described, the wind-shifter is a tool designed to segregate MSW into heavy and light fractions using an airflow mechanism. Its primary purpose is to extract valuable materials from mixed MSW streams, including metals, plastics, paper, wood, and other heavy materials. Figure 5.17 illustrates the wind shifter used in this pilot project.

Figure 5. 17 Wind-Shifter

Based on the findings, the wind-shifter has a processing capacity ranging from 5 to 10 Mg/hour and demonstrates a sorting efficiency of approximately 90%. This indicates its ability to handle a significant amount of MSW and effectively separate the heavy and light fractions.

In this pilot project, the fine shredder operates as the final piece of equipment, transforming the MSW into RDF. It has a crucial role in producing the desired final output that meets the fuel specifications. Implementing the fine shredder in this pilot project aims to ensure that the MSW, having undergone a series of prior processing stages, can be effectively transformed into RDF, which can serve as an AF source. According to the research conducted by Nanda & Berruti (2020), the utilisation of the fine shredder in the MSW processing flow has yielded results that comply with the prescribed fuel quality standards. This finding underlines the critical importance of the fine shredder in efficiently converting MSW into a usable energy resource. Figure 5.18 presents the fine shredder used in this pilot project.

Figure 5. 18 Fine Shredder

The fine shredder produces 50 x 50 mm particle sizes ideal for RDF combustion. In line with the practical situation, it is presumed that smaller particle sizes can enhance the efficiency of burning processes (Peters et al., 2020). Nevertheless, particles of smaller sizes necessitate extra treatment and higher expenses. Thus, they must conform to the final size specifications set by the end user.

Laboratory testing is essential for the comprehensive nature of the analysis. This involves the preparation of the shredded MSW samples according to a strict set of protocols outlined in EN 15443: 2011. Once these samples were prepped, their moisture content was precisely determined as per the standards set in EN 15414-3: 2011. The HHV was determined using a bomb calorimeter and converted to LHV using the formula LHV = HHV - 584 x ((9 x H% +

M%)/100) in kcal/kg, adhering to the procedures specified in EN 15400: 2011. Another critical factor, the ash content, was measured in alignment with EN 15403: 2011 guidelines, ensuring a uniform approach to determining the non-combustible portion of the sample. When it comes to evaluating the total carbon (C), hydrogen (H), and nitrogen (N) content, the process follows the protocols established in EN 15407: 2011, which helps understand the elemental composition of the MSW. For CO_2 emission calculation, the C content should be converted from dry basis to as received, taking into account the moisture content. Next, CO_2 content was calculated using stoichiometry based on the atomic mass ratio. Then, the result was multiplied by the non-biomass fraction since biomass is considered carbon-neutral (Zagaria et al., 2023). Finally, the number was divided by the LHV, resulting in the Kg CO_2/GJ unit.

Oxygen content was calculated by removing the combined percentages of C, H, N, and ash from 100%, a stoichiometric approach. The XRF Epsilon 5, an advanced analyser, accurately measures total sulphur (S), chlorine (Cl), and heavy metals like cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), and copper (Cu), which are important for assessing RDF quality and environmental impact. Figure 5.19 includes the details of Laboratory sample preparation steps.

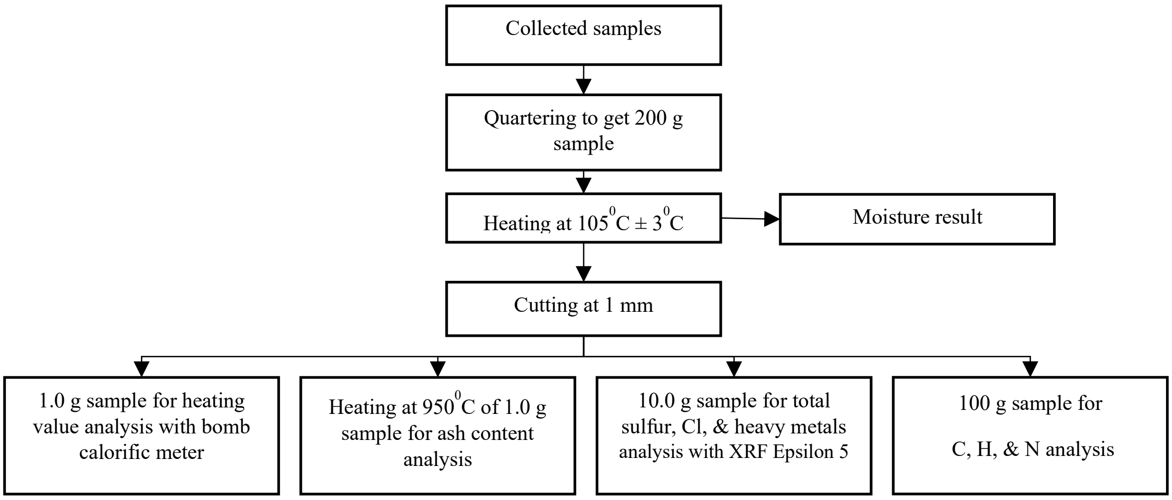

Figure 5. 19 Sample Preparation

Proper sample preparation is crucial as it minimises errors and interferences that can impact the analytical measurement and accuracy of parameters. It ensures the sample is homogeneous and representative of the entire MSW fraction under analysis. The preparation process thus enhances the reliability of data for assessing RDF quality. Additionally, it facilitates the comparison of RDF characteristics across different seasons, reflecting variations in MSW composition. The quantity of samples for each category represents the combined collection from the summer and rainy seasons, facilitating a complete analysis of the seasonal influences on RDF as outlined in Table 5.3. This thorough approach ensures that the RDF produced is consistently of high quality, regardless of seasonal changes in MSW composition.

Table 5. 3 Number of Samples for MSW Characterisation

No	Sample Type	Number of Samples for each parameter (HHV, MC, Ash, S, Cl, Cd, Pb, Cr, Ni, & Cu)	Number of Samples for each parameter (C, H, & N)
A	**Overall MSW**		
1	Jakarta	112	6
2	Bogor	112	6
3	Depok	112	6
4	Bekasi	112	6
B	**Particle Size Distribution**		
1	>200 mm	112	6
2	100-200 mm	112	6
3	80-100 mm	112	6
4	50-80 mm	112	6
5	10-50 mm	112	6
6	<10 mm	112	6
C	**MSW Fraction**		
	Combustible		
1	Organic (garden)	448	20
2	Organic (leftover)	448	20
3	Wood	448	20
4	2D plastics	448	20
5	3D plastics	448	20
6	Paper	448	20
7	Cardboard	448	20
8	Textile	448	20
9	Nappies	448	20
10	Rubber	448	20
	Non-combustible		
1	Fines	448	20

Laboratory tests on a wide array of MSW samples from various cities focus on particle size and combustible fractions. This approach yields a more precise profile of MSW, essential for formulating effective management and policy decisions. The study emphasises combustible elements, examining only fines within non-combustible fractions. Due to equipment limitations, it omits other parameters, sampling solely the readily combustible MSW portion to infer the properties of combustible waste. This is justified as non-combustible fractions, which differ in physical and chemical characteristics, are outside the research scope (Setyono & Sinaga, 2021).

The pilot projects for strategies 1, 2, and 3 were executed 10 times, whereas strategy 4 was implemented 8 times. Specifically, in strategy 1, the moisture content of the MSW materials was assessed 160 times based on measurements taken over 16 days of the bio-drying process across 10 trials. Similarly, for strategy 2, 130 measurements were taken from 13 days of bio-drying during the 10 trials. Table 5.4 below displays the sample counts collected for each pilot project.

Table 5. 4 Number of Samples Taken in the Pilot Projects

No	Sample Type	Number of Trials	Number of Samples for each parameter (HHV, Ash, S, Cl, Cd, Pb, Cr, Ni, & Cu)	Number of Samples for MC	Number of Samples for each parameter (C, H, & N)
A	**Strategy 1**				
1	MSW	10	10	160	5
2	Low-grade RDF <80 mm	10	10	10	5
3	RDF < 50 mm	10	10	10	5
B	**Strategy 2**				
1	MSW	10	10	130	5
2	Low-grade RDF <80 mm	10	10	10	5
3	RDF <50 mm	10	10	10	5
C	**Strategy 3**				
1	MSW	10	10	10	5
2	Low-grade RDF <80 mm	10	10	10	5
3	RDF <50 mm	10	10	10	5
D	**Strategy 4**				
1	MSW	10	8	8	5
2	Low-grade RDF <80 mm	10	8	8	5
3	RDF <50 mm	10	8	8	5

The third part of the investigation focuses on the utilisation of RDF from the pilot project by the cement plant, which commenced following the Laboratory analysis results. The pilot produced two types of RDF: finely shredded RDF under 50 mm and low-grade RDF under 80 mm. Both were delivered to the RDF feed point, handling up to 40 Mg/hour, and then transported to the calciner. Figure 5.20 depicts the RDF feeding process employed by the cement plant.

Figure 5. 20 RDF Utilization in the Cement Plant

Meanwhile, the sorted metals from MSW were distributed to the local community through the Corporate Social Responsibility Division, and the rejected materials were sent to the landfill by the relevant parties.

6. Result and Discussion

6.1 MSW Characterisation

The initial topic addressed in the characterisation of MSW is an overall analysis of MSW from each city across the summer and rainy seasons. A summary of the chemical properties derived from the collective MSW samples is presented in Table 6.1.

Table 6. 1 Overall MSW Chemical Properties

Parameters	Unit	Summer					Rain					Mean
		Jakarta	Bogor	Depok	Bekasi	Mean	Jakarta	Bogor	Depok	Bekasi	Mean	
HHV	MJ/kg	8.8	8.6	8.3	8.3	8.5	8.5	8.2	8.2	8.3	8.3	8.4 ± 0.1
LHV		5.9	5.4	5.1	5.3	5.4	5.9	5.4	5.1	5.3	5.4	5.4 ± 0.1
MC	% wt. (ar.)	52	54	54	56	54	55	56	55	57	56	55 ± 3
Ash	% wt. (db.)	11	11	11	11	12	11	11	12	11	11	11 ± 1
S		0.22	0.23	0.23	0.23	0.2	0.23	0.23	0.24	0.23	0.2	0.2 ± 0.0
Cl		0.40	0.38	0.39	0.42	0.4	0.41	0.38	0.39	0.43	0.4	0.4 ± 0.0
C		49	52	54	52	52	50	56	53	49	52	52 ± 4
H		7	8	6	7	6.8	8	9	7	8	8	7 ± 2
N		1	1	1	1	1	1	1	1	2	1	1 ± 0
O		32	27	28	28	32	29	23	27	30	29	28 ± 1
Cd	mg/kg (db.)	7	7	7	9	8	8	8	8	7	8	8 ± 3
Pb		12	13	11	14	12	12	12	10	13	12	12 ± 7
Cr		6	5	5	6	6	6	6	5	6	6	6 ± 2
Ni		17	16	12	28	18	22	11	22	17	18	18 ± 5
Cu		33	33	34	33	33	32	32	33	33	32	33 ± 9

The table above shows that conditions tend to be drier during the summer, with an average moisture content (MC) of 54%, compared to 56% in the rainy season, indicating a 2% difference, with the latter being moister. Notably, in Jakarta, the lowest MC recorded during the summer was 52%. The average MC across all cities and seasons was 55%, ranging from 53 to 57%. These figures are considered in the discussion regarding selecting the RDF production plant design.

The results of the analysis were similar across the various cities studied. This similarity can be attributed to the parallel characteristics of the populations residing in these areas and the fact that residents often commute between these cities. Another contributing factor is that the samples were taken from intermediate MSW storage facilities, where the MSW has already been preconditioned by processes such as being stored under a roof, mixed, agitated, and removal of valuable materials by waste pickers. Consequently, the results could differ if the samples were taken directly from households.

The results further reveal that key parameters currently do not meet established RDF specifications, requiring additional treatment steps. It is imperative to consider that MC is an incredibly vital parameter in the selection and design of MSW treatment technologies due to its impact on other significant parameters, including heating value and overall system efficiency. This underscores the need for meticulous attention to moisture levels during the MSW to RDF treatment process to enhance the quality and performance of the resulting fuel (He et al., 2022). Subsequently, the discussion extends to the outcomes of the investigation concerning the chemical properties of MSW, juxtaposed with results from other research. This comparison seeks to provide a broader context of the chemical characteristics of the MSW, all of which are presented in Table 6.2 below.

Table 6. 2 MSW Chemical Properties Comparisons

Parameters	Unit	Average of Investigation	Typical
HHV	MJ/kg	8.4	4-16[1,4]
LHV		5.4	5-10[1,4]
MC	% (ar.)	55	20-67[1]
Ash	% wt. (db.)	11	1-20[1,10]
S		0.2	0.1-0.9[1,3,10]
Cl		0.4	0.24-1.9[1,8,9]
C		52	11-54[1,10]
H		7	6-10[1]
N		1	0.04-1.7[1,3]
O		28	30-55[1]
Cd	mg/kg (db.)	7.7	0.3-12[2,6,7]
Pb		12	0.2-312[2,5,7]
Cr		6	0.9-116[2,9]
Ni		18	6-206[2,5,7]
Cu		33	16-552[2,9]

([1]Amen et al., 2021; [2]Azizpour et al., 2020; [3]Cheng et al., 2023; [4]Drudi et al., 2019; [5]Ibrahim et al., 2020; [6]Irfan et al., 2021; [7]Ishchenko, 2019; [8]Ma et al., 2010; [9]Shao et al., 2010; [10]Tursunov et al., 2015)

The table above indicates that the parameters' values, except for heavy metals, are relatively closely aligned. Considerable variation is observed for heavy metals. This discrepancy may be attributed to the quantities of fractions contributing to heavy metal content, such as batteries, lights, and electronic waste. Additionally, the heavy metal content in waste varies depending on the chemical composition of the materials, leaching rates, and environmental conditions such as pH levels (Ishchenko, 2019).

The second outcome of this investigation is the particle size distribution, with the total sample size reaching approximately 46 Mg, where Jakarta contributed 12 Mg, Bogor 11 Mg, Depok 11 Mg, and Bekasi 12 Mg. Figure 6.1, shown below, provides the analysis of size distribution.

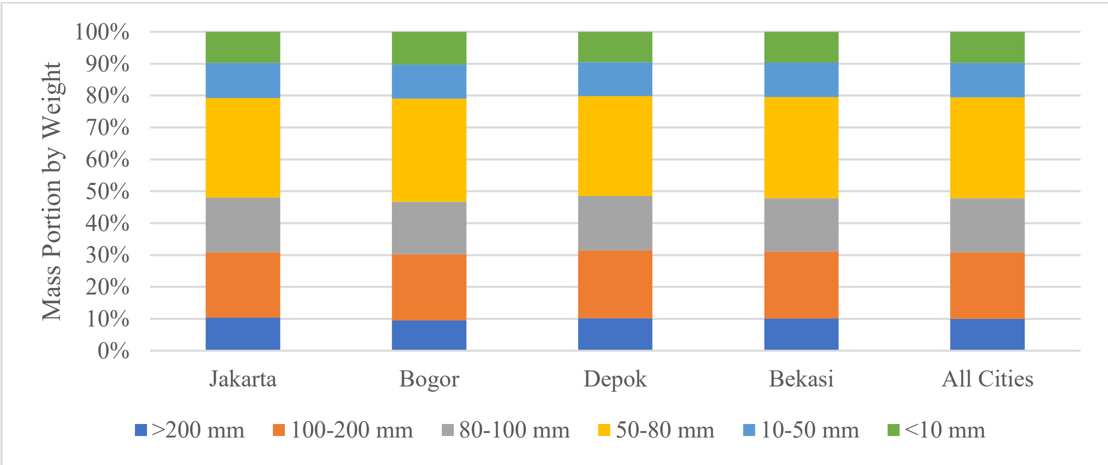

Figure 6. 1 Particle Size Distribution in mm

The average particle size distribution shows that particles <10 mm constitute 9.8%, particles ranging from 10-50 mm makeup 10.8%, those from 50-80 mm account for 31.6%, particles sized 80-100 mm make up 16.9%, those within 100-200 mm are 20.9%, and particles larger than 200 mm comprise 10%. Additionally, the total for sizes larger than 80 mm is 47.8%, while smaller than 80 mm represents 52.2%. The 80 mm size marks the optimal combustion threshold in cement plants. For comparison, particle size measurements in Jordan yielded 31.6% for sizes >100 mm, 31.0% for 50-100 mm, 22.8% for 10-50 mm, and 13.6% for sizes <10mm (Al-Hajaya et al., 2021).

The analysis moves forward to disclose the findings from the fractions, such as combustible and non-combustible materials for each particle size distribution. Four hundred kg of samples for each particle size category were collected from every city, resulting in a combined sum of 2.4 Mg of samples across six categories. This is useful for identifying which particle size distributions have a higher propensity to contain more readily combustible materials.

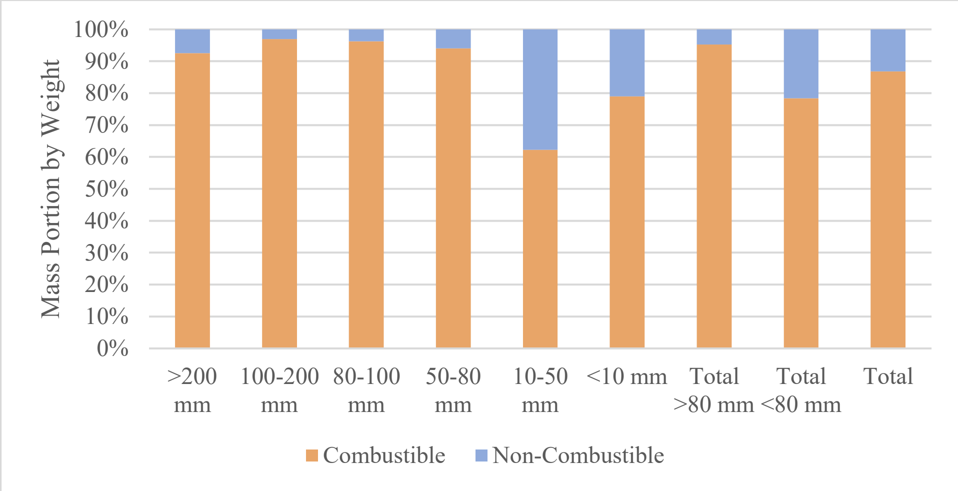

Figure 6. 2 Fraction of Each Particle Size Distribution

Figure 6.2 above focuses on the size distribution of combustible and non-combustible particles. The dominant fraction across all sizes was combustible. However, combustible fractions at the 10-50 mm size were 62%, and those smaller than 10 mm were 79%, still prevalent but significantly lower than other sizes due to substantial inert material. Figure 6.2 shows that the combustible materials of the MSW make up 95% of the portion for materials with sizes larger than 80 mm. In contrast, the proportion of combustible materials drops to 78% for materials smaller than 80 mm. If the size spectrum is taken into account, 87% of the MSW consisted of combustible material, with the remaining 13% being non-combustible. In a study undertaken in Jordan, the fraction of MSW found to be combustible was recorded at 92% for particles >100 mm, 87% for those in the 50-100 mm size range, 95% for the range of 10-50 mm, and notably, 80% for the finest category of particles smaller than 10 mm, indicating a significant presence of combustible material even in the smallest measured MSW size fractions (Al-Hajaya et al., 2021).

Table 6. 3 Biomass Fraction of Each Particle Size Distribution

Fraction	>200	100-200	80-100	50-80	10-50	<10	Total >80	Total <80	Total
Biomass	70%	56%	68%	66%	54%	71%	65%	64%	64%
Non-biomass	30%	44%	32%	34%	46%	29%	35%	36%	36%

Next, using the same data, the biomass content can be estimated based on the summation of the organic (garden), organic (leftover), wood, paper, and cardboard fractions. Table 6.3 below provides a detailed elucidation of the biomass content for each specific fraction. Biomass is considered a carbon-neutral energy source because the CO_2 released during its combustion is roughly equivalent to the CO_2 absorbed by the plants during photosynthesis, making it a net zero-carbon option on the path to carbon reduction (Zagaria et al., 2023). Therefore, for calculating CO_2 emissions, this biomass content can reduce the emission factor when combusted.

Table 6. 4 Chemical Properties of Each Particle Size Distribution

Parameters	**Unit**	**>200 mm**	**100-200 mm**	**80-100 mm**
HHV	MJ/kg	4.6 ± 1.0	10.7 ± 2.4	7.4 ± 1.6
LHV		3.0 ± 1.0	7.7 ± 2.4	4.6 ± 1.6
MC	% wt. (ar.)	34 ± 8	61 ± 13	66 ± 21
Ash	% wt. (db.)	10 ± 1	16 ± 1	6 ± 1
S		0.2 ± 0	0.2 ± 0	0.2 ± 0
Cl		0.1 ± 0	0.4 ± 0	0.7 ± 0
C		46 ± 4	67 ± 12	54 ± 29
H		3 ± 5	7 ± 12	5 ± 9
N		0.7 ± 0	1.0 ± 0	1.8 ± 1
O		40 ± 2	9 ± 5	31 ± 7
Cd	mg/kg (db.)	1 ± 1	3 ± 1	4 ± 4
Pb		4 ± 0	6 ± 2	6 ± 4
Cr		1 ± 0	5 ± 1	5 ± 1
Ni		2 ± 0	25 ± 16	9 ± 6
Cu		6 ± 1	30 ± 5	48 ± 5

Parameters	**Unit**	**50-80 mm**	**10-50 mm**	**<10 mm**	**Weighted average**
HHV	MJ/kg	10.7 ± 1.0	5.1 ± 1.4	3.7 ± 0.8	8.2
LHV		7.3 ± 1.0	2.5 ± 1.4	2.8 ± 0.8	5.5
MC	% wt. (ar.)	61 ± 16	50 ± 12	17 ± 2	54
Ash	% wt. (db.)	16 ± 2	2 ± 1	0 ± 2	11
S		0.3 ± 0	0.3 ± 0	0.3 ± 0	0.3
Cl		0.4 ± 0	0.7 ± 0	0.1 ± 0	0.4
C		63 ± 8	34 ± 6	24 ± 4	54
H		9 ± 5	6 ± 10	2 ± 3	6
N		1.7 ± 0	1.6 ± 0	0.2 ± 0	1.3
O		10 ± 4	55 ± 4	72 ± 2	27
Cd	mg/kg (db.)	8 ± 3	8 ± 2	1 ± 1	5
Pb		12 ± 3	16 ± 3	1 ± 0	8
Cr		5 ± 1	5 ± 1	12 ± 2	5
Ni		9 ± 4	6 ± 1	2 ± 0	11
Cu		20 ± 3	9 ± 1	19 ± 2	24

Table 6.4 methodically outlines the chemical properties pertinent to each fraction of MSW. It details the chemical properties and composition of MSW samples across various particle sizes and the weighted average for the properties measured. The HHV ranged from a low of 3.7 MJ/kg for the smallest particles (<10 mm) and peaked at 10.7 MJ/kg for the 100-200- and 50-80-mm sizes, respectively, indicating greater energy potential in the larger particles. The MC

of all sizes was consistent at >50%, except for particle sizes of <10 mm and >200 mm, where it dropped to 17% and 34%, respectively.

The ash percentage fluctuated across particle sizes, with the smallest fractions displaying low percentages while the ranges of 100-200 mm and 50-80 mm exhibited higher values. The contents of S and Cl showed less variation across the different sizes, yet the levels of heavy metals displayed more significant fluctuations, with particular sizes having considerably higher concentrations. For example, Ni stood out with a 25 mg/kg concentration in the 100-200 mm size range. The elements C, H, N, and O, factored into the oxygen calculation, demonstrated a similar variability pattern. The table's final column presents a weighted average for each parameter, providing a summary that incorporates the diverse proportions of particle sizes found within the MSW stream. This variation in data underscores the intricate nature of MSW and underlines the importance of thorough analysis for its effective management and treatment. Differences in particle size and quality are to be expected, given the inherently complex composition of MSW (Tanguay-Rioux et al., 2020).

Figure 6.3 shows results of MSW fraction analysis from collected MSW samples, totalling 967 Mg. This significant amount was due to the scale of collection, which is essential for evaluating MSW because it affects the research outcomes. The data provided a solid foundation for understanding the MSW stream's variety, which is key to creating targeted MSW management strategies and models for strategic advice. Studying a sizable, representative samples reveal important trends and patterns vital for enhancing sorting, recycling, and conversion in MSW management systems (Zhou et al., 2015).

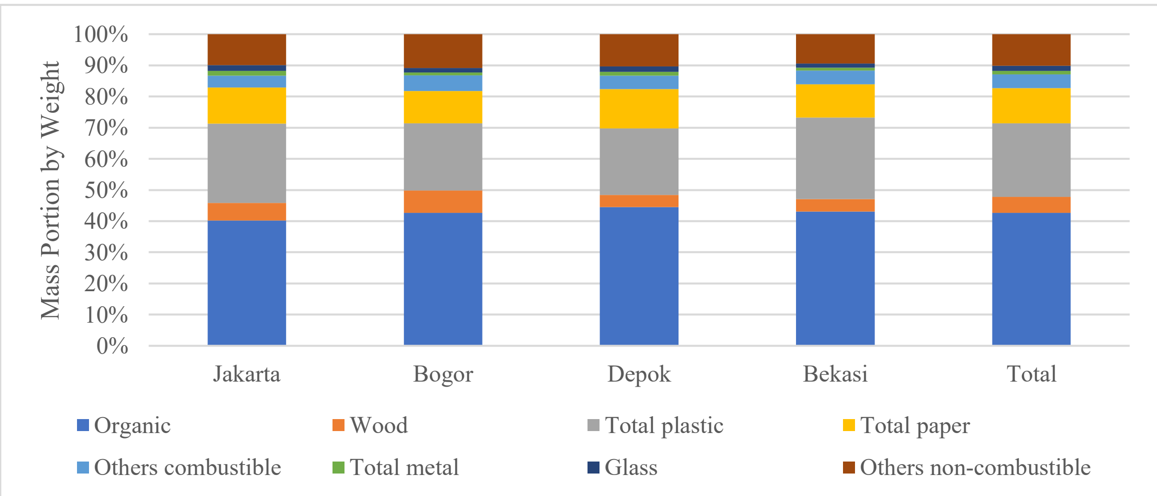

Figure 6. 3 Summary of MSW Fractions Composition

Figure 6.3 provides a detailed breakdown of MSW fraction percentages for selected regions. The data presented here serve as a summary; the complete detailed data can be found in Appendix 2. For organic waste, the proportions were relatively high across all cities, with Jakarta reaching 40%, which rose slightly in Bogor and Depok to 43% and 45%, respectively, and averaged out at 43% across the total region. Wood waste accounted for a lower fraction, ranging from 4% in Depok and Bekasi to 7% in Bogor, with a regional average of 5%. In addition, an additional characterisation was performed on 77 Mg of MSW samples from Jakarta, identifying 229 kg of PVC, constituting 0.3% of the total MSW. Compared to other types, PVC waste in Indonesia is very low, constituting less than 0.5% of the plastic fraction (Nurito et al., 2022; Widiyatmoko et al., 2015). In comparison, in the Nordic region, PVC waste is 1.75% of the plastic fraction (Miliute-Plepiene et al., 2021). The PVC fraction of the total waste generated from this investigation was 0.07% of the total MSW, where the total plastic fraction was 24%.

The presence of plastic varied across different regions. In Jakarta and Bekasi, the proportion of plastic was notably higher, accounting for 25% and 26%, respectively. In contrast, the plastic percentage in Bogor and Depok was consistent, with a value of 21%. This diversity yielded an aggregate regional mean of 24%, notably exceeding Indonesia's average plastic content benchmark of 19%. This elevated prevalence within the surveyed domain is attributable to the wasteful behaviour of the Jabodebek populace, specifically in their usage of plastic packaging. This is consistent with other data on plastic content in Jakarta, which was reported as 23% (BPS Jakarta, 2023). Paper waste ranged from 10% in Bogor to 13% in Depok, averaging 11%. Combustibles were at 4%, while metals and glass constituted up to 2%. Other non-combustibles varied slightly but averaged 10% regionally.

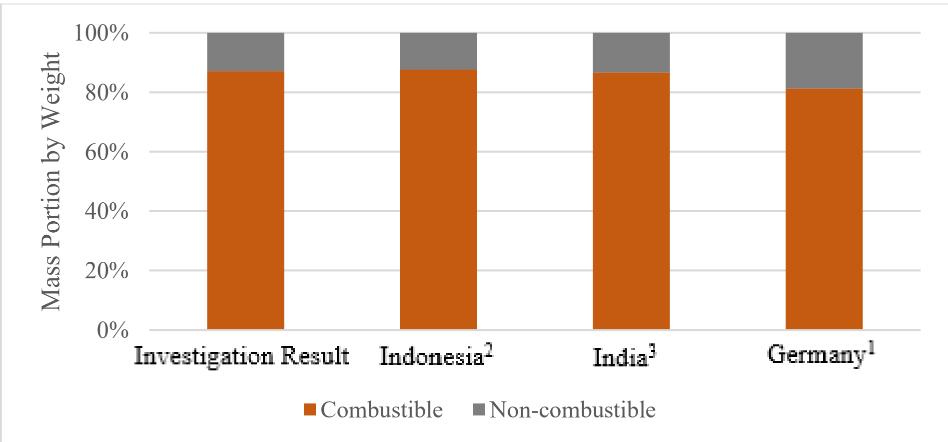

Figure 6. 4 Comparison of Combustible Fraction of MSW
([1]BMUV, 2023; [2]KLHK, 2023; [3]Singhal et al., 2022)

The results depicted in Figure 6.4 show the varying composition of MSW fractions across different regions. Combustible materials accounted for a significant portion of the MSW, with a value of 87%, closely resembling the proportions reported in Indonesia and India, recorded at 88% and 87%, respectively. This similarity in high combustible content between India and Indonesia may reflect commonalities in population habits, such as a high degree of mixed MSW, often resulting from less stringent sorting practices at the source (World Bank, 2023c). Germany's MSW profile indicates a lower combustible content at 81% and a higher non-combustible fraction at 19%, hinting at a sophisticated MSW management system that encourages segregation, leading to less mixed MSW and enhanced recycling and energy conversion treatment (BMUV, 2023). Efficient source separation results in a reduced presence of combustible materials, such as plastics, in MSW streams.

Table 6. 5 Biomass Fraction of MSW

Fractions	Jakarta	Bogor	Depok	Bekasi	Total
Biomass	59%	61%	62%	59%	60%
Non-biomass	41%	39%	38%	41%	40%

The estimated biomass content for each region is presented in Table 6.5. The table showcases biomass contents predominantly hovering around 60%, with Jakarta and Bekasi at 59%, Bogor at 61%, and Depok at the highest at 62%. Meanwhile, the chemical properties of the MSW fractions are detailed in Table 6.6 below.

Table 6. 6 Chemical Properties of Each MSW Fractions

No	MSW Fractions	HHV (MJ/kg)	LHV (MJ/kg)	Moisture (% wt. ar.)	Ash (% wt. db.)	S (% wt. db.)
A	Combustible					
1	Organic (garden)	5.0 ± 0.5	1.6 ± 0.5	77 ± 7.3	16 ± 1.4	0.1 ± 0.01
2	Organic (leftover)	4.3 ± 0.4	1 ± 0.4	78 ± 6.7	17 ± 1.7	0.5 ± 0.05
3	Wood	7.5 ± 0.8	4.9 ± 0.8	47 ± 4.6	5 ± 0.6	0.1 ± 0.01
4	2D Plastics	17.6 ± 1.6	13.6 ± 1.6	49 ± 5.6	6 ± 0.5	0.1 ± 0.01
5	3D Plastics	21.5 ± 2.3	17.4 ± 2.3	32 ± 3.7	9 ± 0.7	0.2 ± 0.02
6	Paper	11.2 ± 1.2	8.3 ± 1.2	52 ± 4.9	3 ± 0.3	0.2 ± 0.02
7	Cardboard	11.6 ± 1.2	9.1 ± 1.2	45 ± 4.5	9 ± 1	0.1 ± 0.01
8	Textile	11.6 ± 1.1	8.7 ± 1.1	53 ± 5.5	13 ± 1.3	0.1 ± 0.01
9	Nappies	4.7 ± 0.5	2.1 ± 0.5	57 ± 5.7	31 ± 3	0.2 ± 0.02
10	Rubber	28.5 ± 2.9	25.7 ± 2.9	4 ± 0.6	3 ± 0.4	0.4 ± 0.04
B	Non-combustible					
1	Fines	1.2 ± 0.1	0 ± 0	16 ± 1.7	47 ± 5.1	0.4 ± 0.04
C	Weighted average	8.5	5.6	55	11	0.2

Table 6.6 Chemical Properties of Each MSW Fractions (continue)

No	MSW Fractions	Cl (% wt. db.)	C (% wt. db.)	H (% wt. db.)	N (% wt. db.)	O (% wt. db.)
A	Combustible					
1	Organic (garden)	0.3 ± 0.03	56 ± 5	7 ± 0.5	1.7 ± 0.2	14 ± 1.2
2	Organic (leftover)	0.8 ± 0.08	48 ± 7	6 ± 0.7	1.8 ± 0.2	20 ± 1.6
3	Wood	0.0 ± 0.00	47 ± 4	7 ± 0.6	0.3 ± 0.1	40 ± 0.9
4	2D Plastics	0.3 ± 0.02	64 ± 7	13 ± 1.5	0.1 ± 0.0	16 ± 1.4
5	3D Plastics	0.1 ± 0.01	72 ± 7	15 ± 1.8	0.1 ± 0.0	5 ± 1.6
6	Paper	0.1 ± 0.09	44 ± 4	7 ± 0.6	0.4 ± 0.0	45 ± 0.8
7	Cardboard	0.1 ± 0.08	40 ± 4	6 ± 0.6	0.6 ± 0.1	41 ± 1.0
8	Textile	0.1 ± 0.01	49 ± 6	7 ± 1.1	3.2 ± 0.4	22 ± 1.4
9	Nappies	0.2 ± 0.01	42 ± 4	6 ± 0.6	2.7 ± 0.2	8 ± 1.2
10	Rubber	0.1 ± 0.01	53 ± 6	12 ± 1.1	0.9 ± 0.1	29 ± 1.2
B	Non-combustible					
1	Fines	0.1 ± 0.01	26 ± 3	3 ± 0.3	0.2 ± 0.0	11 ± 1.4
C	Weighted average	0.4	47	7	0.9	33

Table 6.6 delves into the analysis of different MSW fractions, detailing their chemical properties. In the combustible fraction, garden organic waste represented 10% of the MSW and had an HHV of 5.0 MJ/kg, with its energy potential dampened by high MC (77%). Leftover organic material was more prevalent, constituting 33% of the MSW, yet it offered a lower HHV of 4.3 MJ/kg due to similar moisture levels. Wood, which accounted for 5%, had a higher energy content with an HHV of 7.5 MJ/kg, benefiting from a relatively lower MC. Significant volumes of plastics were present, at 22% for 2D plastics and 2% for 3D plastics, showcasing much higher HHV values of 17.6 and 21.5 MJ/kg, respectively, affirming their values in terms of calorific potential. Paper and cardboard were modestly represented and exhibited moderate HHV values indicative of their lower MC than organic waste. Textiles, nappies, and rubber were less pronounced in the MSW stream but varied greatly in HHV, with rubber demonstrating a remarkably high value due to its low MC. The non-combustible fractions included fine waste, making up 4%. As anticipated, these fractions maintained a minimal HHV, congruent with their limited or lack of combustible materials. The collective weighted average for all MSW fractions reflected the combustible potential of the MSW, registering an HHV of 8.5 MJ/kg and an average MC of 55%, resulting in an LHV of 5.6 MJ/kg. The content of plastics and paper emerges as a crucial factor for producing high-calorific-value RDF, indicating that higher fractions of these materials will lead to a correspondingly higher caloric value of the RDF (Tihin et al., 2023).

Combustible fractions like garden organics and leftover organics featured ash content of 21% and 22%, respectively, alongside minor S and Cl percentages. Notably, the carbon content was significant across the board, with 2D and 3D plastics showing 64% and 72% values, indicating high potential energy yield. Materials like wood and paper also showed substantial carbon levels but less ash, while textiles and nappies had higher ash, suggesting a mix of combustible and inert elements. Non-combustible waste, represented by fines, had a high ash content of 60%, expectedly paired with lesser carbon presence, reflecting its limited energy recovery potential. The weighted average across all fractions pointed to an ash content of 11% and carbon presence of 47%, illustrating the combustible nature of the MSW and its implications for management and recovery. Carbon content is essential for evaluating each MSW fraction's energy generation potential and estimating CO_2 emissions, and it is critical for environmental impact assessments and carbon footprints (Wienchol et al., 2020).

Within the combustible fractions, S and Cl contents were low across most materials, with organic leftovers showing a slightly higher Cl concentration at 0.8%. Even though the values were low, monitoring both parameters are crucial because they could form harmful emissions during combustion and cement manufacturing processes. Nitrogen, hydrogen, and oxygen varied among the fractions, indicative of the different organic compounds comprising the MSW. For example, 3D plastics had a remarkably high hydrogen content at 15%, while organics and textiles had higher nitrogen readings, with textiles at 3.2% standing out. Oxygen content was considerable in most organic fractions due to the prevalence of oxidizable materials, with garden organics and leftover organics showing oxygen content of 14% and 20%, respectively.

In the non-combustible fraction fines, the S and Cl values remained low, akin to combustibles. At the same time, nitrogen, hydrogen, and oxygen followed the previous patterns, supporting a low energy profile for these materials. The carbon content and elemental analysis results are similar to the results of an investigation in Singapore (Zhao et al., 2016).

Next, Table 6.7 showcases the properties of heavy metals in each MSW fraction, serving as a continuation of the previous table. This heavy metal information is crucial for grasping the possible environmental effects of heavy metal accumulation in cement products that use RDF (Cipurkovic et al., 2014).

Table 6. 7 Heavy Metal Properties of Each MSW Fractions

No	MSW Fractions	Cd (mg/kg db.)	Pb (mg/kg db.)	Cr (mg/kg db.)	Ni (mg/kg db.)	Cu (mg/kg db.)
A	Combustible					
1	Organic (garden)	16 ± 6	13 ± 3	5 ± 1	2 ± 1	9 ± 3
2	Organic (leftover)	12 ± 3	12 ± 3	5 ± 1	3 ± 1	17 ± 3
3	Wood	1 ± 0	1 ± 0	1 ± 0	1 ± 0	4 ± 1
4	2D Plastics	2 ± 0	5 ± 1	4 ± 1	50 ± 20	66 ± 3
5	3D Plastics	3 ± 0	5 ± 1	1 ± 1	13 ± 1	18 ± 2
6	Paper	1 ± 0	6 ± 1	1 ± 1	3 ± 1	9 ± 1
7	Cardboard	1 ± 0	3 ± 1	2 ± 1	2 ± 1	7 ± 1
8	Textile	2 ± 0	3 ± 1	3 ± 1	6 ± 1	12 ± 1
9	Nappies	2 ± 1	1 ± 1	2 ± 1	2 ± 1	5 ± 1
10	Rubber	1 ± 0	2 ± 1	7 ± 1	5 ± 1	11 ± 1
B	Non-combustible					
1	Fines	1 ± 0	1 ± 1	12 ± 1	1 ± 1	13 ± 1
C	Weighted average	6	7	4	13	23

Heavy metals values in the combustible fraction of MSW drew concerns, particularly within garden organics, which harboured 16 mg/kg of Cd and 13 mg/kg of Pb, clearly signifying the potential for contamination. Mirroring this pattern, leftover organics displayed comparable Pb levels, albeit with lesser Cd contents. When juxtaposing organics with wood, it is clear that wood is significantly less implicated in heavy metal contamination, embodying its comparatively cleaner profile across the spectrum of tested heavy metals. This distinction is relevant in assessing wood waste's recyclability and environmental implications compared to more contaminated organics.

On the other hand, the total plastic fractions exhibited a conspicuous surge in heavy metal content. Notably, Ni content was considerable at 50 mg/kg in 2D plastics and 13 mg/kg in 3D plastics. Cu presented similarly high concentrations, with 66 mg/kg in 2D plastics and 18 mg/kg in 3D plastics. Heavy metals in plastics are often due to various additives, such as plasticizers and pigments (Turner & Filella, 2021). Moreover, despite being primarily organic, paper and cardboard contained trace amounts of heavy metals, including up to 6 mg/kg of Pb in paper. The moderate levels found in textiles and nappies align with the diverse range of materials they comprised. Moreover, non-combustible fractions such as fines revealed heavy metal contamination, with Cr concentration at 12 mg/kg. The presence of heavy metals in various MSW fractions is consistent with studies from India, showing a wide range of heavy metal concentrations. This reflects a widespread issue in managing MSW globally (Paramita et al., 2018; Sood & Sharma, 2019).

Table 6. 8 Comparison of Chemical Property Results

Parameters	Unit	Overall MSW Sample	Weighted Average by Mass	
			Particle Size Distribution Sample	MSW Fractions Sample
HHV	MJ/kg	8.4	8.2	8.5
LHV		5.4	5.5	5.6
Moisture	% wt. (ar.)	55	54	55
Ash	% wt. (db.)	11	11	11
S		0.2	0.3	0.2
Cl		0.4	0.4	0.4
C		52	54	47
H		7	6	7
N		1.1	1.3	0.9
O		28	27	33
Cd	mg/kg (db.)	8	5	6
Pb		12	8	7
Cr		6	5	4
Ni		18	11	13
Cu		33	24	23

Table 6.8 depicts a comparison of the chemical properties across three sample groups, namely the overall MSW analysis, which includes various analyses of MSW, and the weighted average of mass based on the percentage of particle size distribution and the specific fractions of MSW. The table shows that the HHV is highest in the MSW fractions at 8.5 MJ/kg, slightly above the overall MSW and the particle size distribution weighted average values of 8.4 MJ/kg and 8.2 MJ/kg, respectively. This trend is similar but reversed for the LHV, where the LHV of the weighted average for MSW fractions was 5.6 MJ/kg, marginally higher than the overall MSW at 5.4 MJ/kg.

The MC remained uniform at 55% for the overall MSW and the MSW fractions, with a minimal decrease to 54% for particle size distribution. The ash content recorded similar values, approximately 11%, across all three sample groups. S content was marginally higher in the particle size distribution at 0.3%, while Cl was the same across all categories at 0.4%. Carbon content showed variability, with overall MSW at 52% compared to 54% in particle size distribution and then dropping to 47% in MSW fractions. For hydrogen content, overall MSW and MSW fractions had a value of 7%, slightly higher than the particle size distribution sample of 6%. Nitrogen was consistent at approximately 1% across the measures. On the other hand, the oxygen content exhibited the most substantial variation, increasing from 27% in particle size distribution to 33% in MSW fractions. Heavy metals demonstrated different levels among the categories. Overall, MSW tended to have higher concentrations of these metals, with significant differences indicated in the weighted average for particle size distribution, suggesting a dilution effect or a difference in the presence of these elements within the various particle sizes. The analysis results from the MSW fractions were employed for modelling because they encompassed the largest sample population among the categories, representing approximately 76%. This significant proportion of the dataset ensures a more representative and robust model that accurately reflects the characteristics of the MSW being investigated.

6.2 RDF Production Pilot Project

The first pilot project to process MSW into RDF, strategy 1, was implemented simultaneously on two bays, utilising a bio-drying process lasting 16 days to achieve an MC target of 30% with a wheel loader serving as a turner that turned the heap every 2-3 days. Each bay required 100 Mg of MSW for a single bio-drying process. In total, 10 trials were conducted, spanning a cumulative period of 90 days, which commenced in January 2023. The depiction in Figure 6.5 outlines the process and material balance of strategy 1.

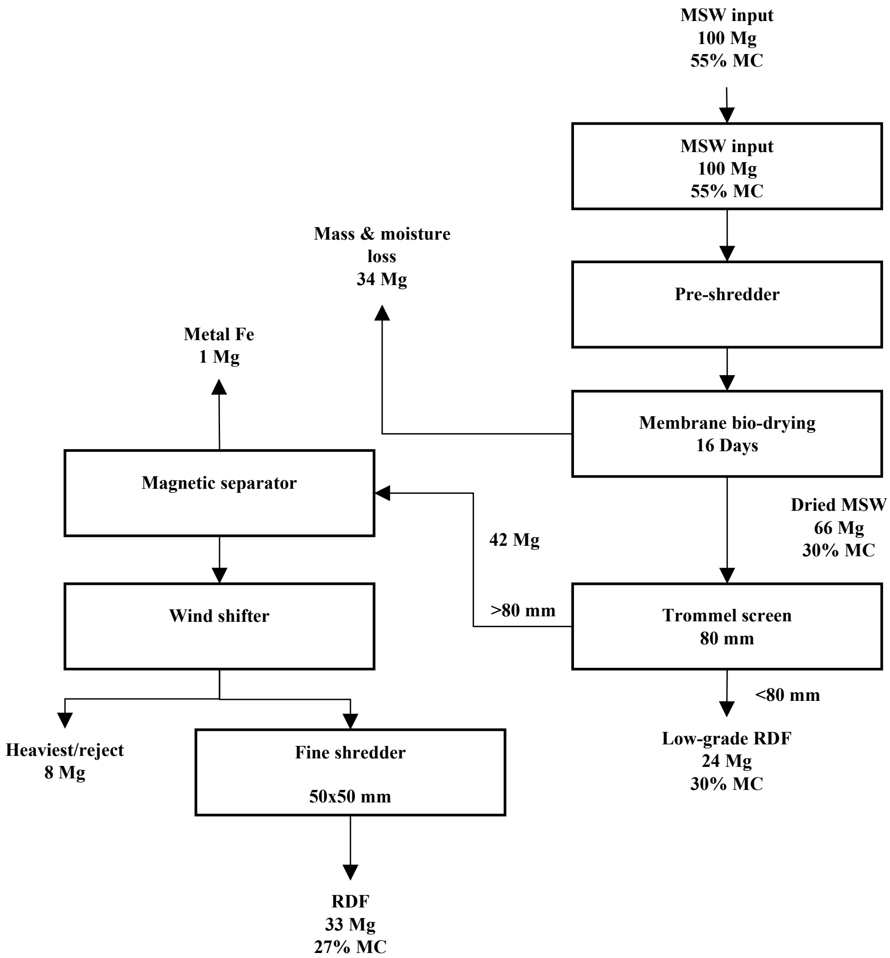

Figure 6. 5 Processes and Mass Flow in Strategy 1

The correlation between the mean temperature and the moisture level in strategy 1 is illustrated in Figure 6.6, with the temperature data recorded from the core of the sample pile.

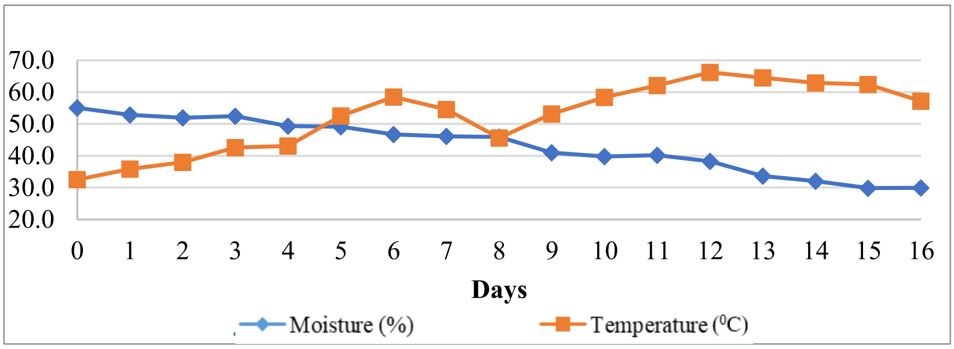

Figure 6. 6 Temperature and Moisture Content Samples of Strategy 1

The bio-drying process showed that temperatures steadily rose over the initial days, reaching an elevated stage between days 5 and 14, where the process achieved its peak thermophilic activity. The average highest temperature between day 5 and day 14 was 58°C. The average temperature throughout the entire 16 days was 53°C, and the highest recorded temperature was 66°C on day 12. The bio-drying process was incomplete and could be extended to achieve a lower MC of 20% (Contreras-Cisneros et al., 2021). However, the MC target was set higher to 30% to shorten the process duration and provide future capital expenditure savings.

Table 6. 9 Result of Strategy 1

Parameters	**Unit**	**MSW Input**	**Bio-drying Output**	**Low-grade RDF**	**RDF**
HHV	MJ/kg	8.5 ± 0.7	19.3 ± 0.1	9.5 ± 0.4	19.3 ± 0.8
LHV	MJ/kg	5.6 ± 0.7	16.4 ± 0.1	7.4 ± 0.1	16.5 ± 0.8
MC	% wt. (ar.)	55 ± 1	30 ± 1	30 ± 2	27 ± 1
Ash	% wt. (db.)	11 ± 1	18 ± 1	29 ± 1	18 ± 1
S		0.22 ± 0.06	0.42 ± 0.05	0.48 ± 0.09	0.38 ± 0.02
Cl		0.39 ± 0.05	0.58 ± 0.04	0.67 ± 0.08	0.62 ± 0.04
C		-	-	39 ± 2	54 ± 2
H		-	-	6.3 ± 1	10 ± 1
N		-	-	0.7 ± 0.2	0.6 ± 0.1
O		-	-	24 ± 1	17 ± 1
Cd	mg/kg (db.)	-	-	9 ± 1	10 ± 1
Pb		-	-	13 ± 1	13 ± 1
Cr		-	-	10 ± 1	13 ± 1
Ni		-	-	20 ± 2	21 ± 2
Cu		-	-	34 ± 6	28 ± 4

Table 6.9 details the analysis results derived from the executed strategy. After bio-drying, the output was sorted and refined, resulting in two products: low-grade RDF and higher-quality RDF. The former had a higher HHV and ash content, while the latter had less moisture.

In strategy 2, the drying process involved bio-drying in a sunlight-penetrated storage, with two batches processed over 13 days to reach 30% of MC. Each batch used 100 Mg of MSW, and 10 trials over 75 days started in April 2023. Figure 6.7 illustrates the workflow of strategy 2.

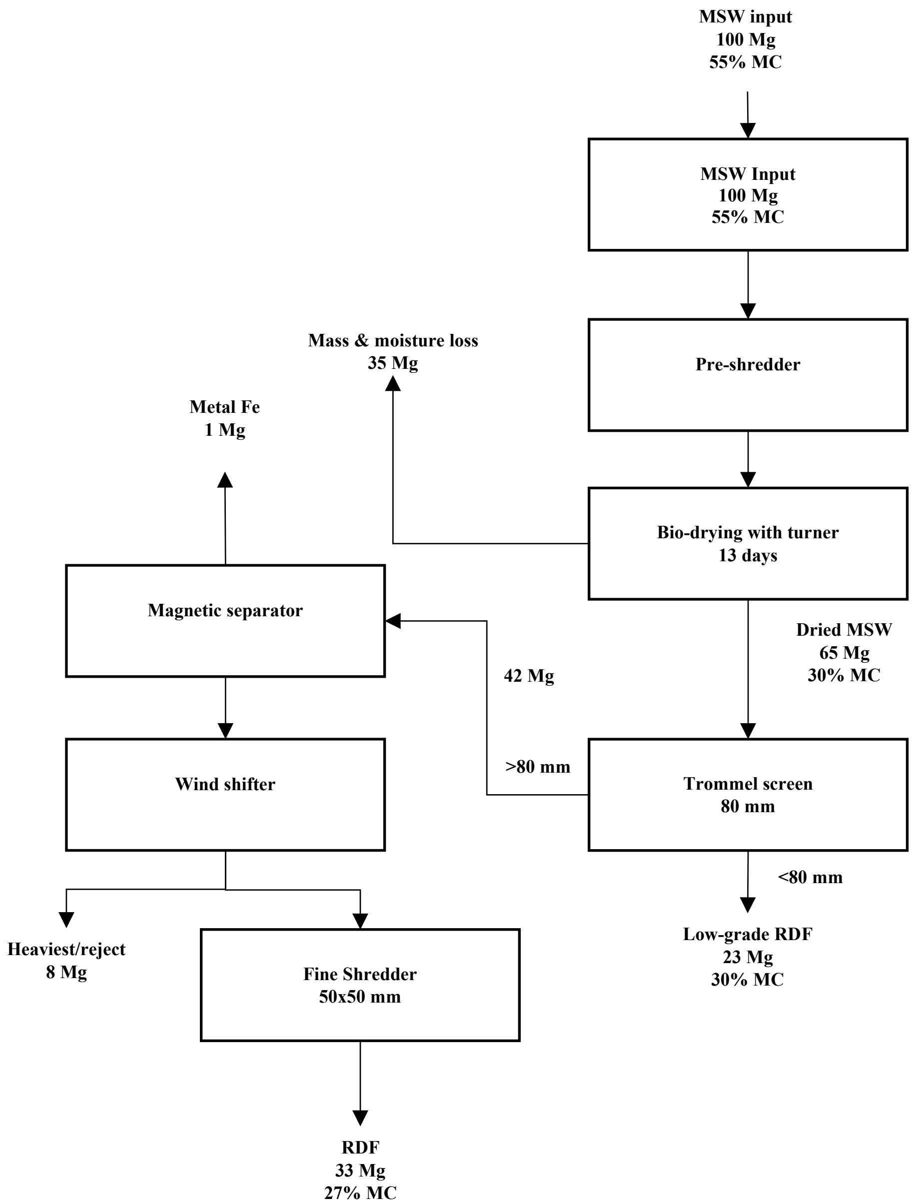

Figure 6. 7 Processes and Mass Flow in Strategy 2

On the following page, Figure 6.8 displays a graph illustrating the correlation between temperature and MC averages in Strategy 2, where temperature readings were recorded at the center of the heap.

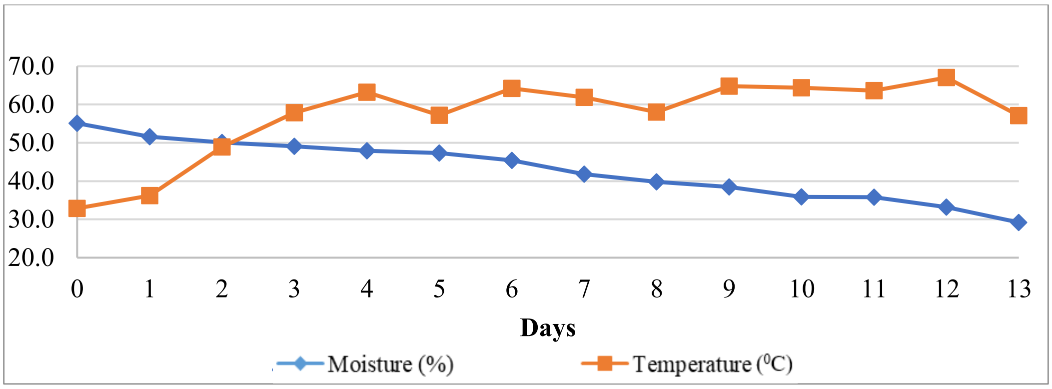

Figure 6. 8 Relation Between Temperature & MC in Strategy 2

The average temperature over the drying period was approximately 57°C, while the average of the highest temperatures during this bio-drying process was around 62°C. The range of days with the highest temperatures appeared to start from day 3, where the temperature reached 58°C and continued until day 13. The peak temperature of 67°C was achieved on day 12. These values were useful for assessing the efficiency of the bio-drying process in reducing moisture content, which was shown to decrease alongside increasing temperatures up to the last recorded day. The solar drying process accelerated the bio-drying process as the heat helped to dry the heap's surface and quicken microbial activity (Noori et al., 2022). As a result, achieving 30% MC only required 13 days, 3 days faster than in strategy 1.

Table 6. 10 Result of Strategy 2

Parameters	Unit	MSW Input	Bio-drying Output	Low-grade RDF	RDF
HHV	MJ/kg	8.4 ± 0.4	20 ± 0.1	9.5 ± 1.1	19.6 ± 0.6
LHV	MJ/kg	5.6 ± 0.1	17.0 ± 0.1	7.4 ± 0.1	16.6 ± 0.6
MC	% wt. (ar.)	55 ± 0.7	29 ± 0.0	30 ± 2	27 ± 2
Ash	% wt. (db.)	11 ± 0.26	18 ± 1	30 ± 1	19 ± 1
S		0.21 ± 0.09	0.41 ± 0.01	0.43 ± 0.04	0.40 ± 0.07
Cl		0.42 ± 0.07	0.82 ± 0.03	0.66 ± 0.07	0.67 ± 0.07
C		-	-	42 ± 1	55 ± 2
H		-	-	6 ± 1	10 ± 1
N		-	-	1 ± 0.01	1 ± 0.02
O		-	-	20 ± 1	14 ± 1
Cd	mg/kg (db.)	-	-	9 ± 1	17 ± 1
Pb		-	-	18 ± 1	16 ± 1
Cr		-	-	11 ± 1	12 ± 1
Ni		-	-	18 ± 2	20 ± 2
Cu		-	-	28 ± 4	32 ± 4

Table 6.10 presents the outcomes of strategy 2. After bio-drying, the dried MSW was separated into low-grade RDF and RDF using a trommel, with further refinement through a magnetic separator, wind sifting, and a fine shredder. The RDF demonstrated slightly better potential with lower moisture content and ash compared to low-grade RDF. The results were similar to those in strategy 1, with a notable difference in MC. In strategy 2, the MC for RDF ranged from 25% to 29%, compared to 26% to 28% in strategy 1.

Next, strategy 3 was characterized by its exclusive reliance on mechanical treatment without any drying processes. This method was applied to process 100 Mg of MSW in each batch. The strategy was tested across 10 trials or batches, with each trial spanning 1-1.5 days per batch. The pilot scale project was commenced in December 2023. Figure 6.9 illustrates the workflow in strategy 3, as depicted below.

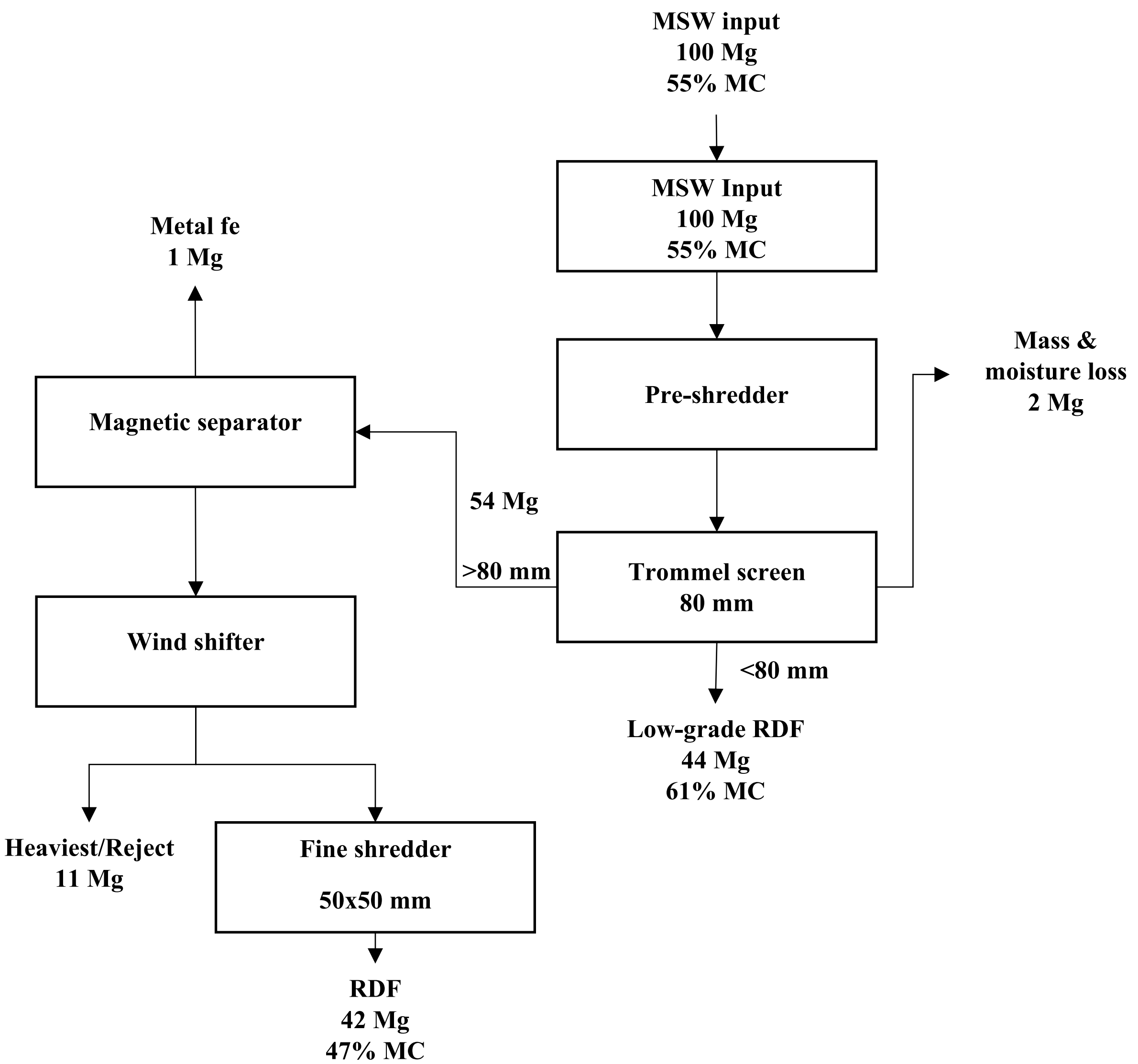

Figure 6. 9 Processes and Mass Flow in Strategy 3

Based on the principles of mechanical treatment, strategy 3 aligns with strategies 1 and 2, with the exception of the special drying process. The trial's findings indicated that the trommel screen's performance in processing material decreased by approximately 50% compared to strategies 1 and 2. This reduction was attributed to the wet condition of the processed material, which retained an MC of 55%. The study noted that the trommel screen's performance significantly dropped from an estimated 8-10 Mg to merely 3-7 Mg. This downturn was primarily due to the considerable spillage occurring within the equipment, which directly resulted from the high moisture levels in the material being processed. This wet condition made it challenging to efficiently separate the material, resulting in suboptimal MSW reduction.

Additionally, the performance of the fine shredder also decreased significantly. Initially capable of processing about 5-10 Mg/hour, the performance of this equipment dropped to only 1-4 Mg/hour, or approximately 20-30% of its original capacity. The moisture in the material also contributed to the diminished efficiency. The dampness caused the MSW to clump together and obstruct the machinery, impeding the effective operation of shredding processes. Effectively controlling the moisture levels is essential to optimise the shredder and the overall mechanical performance (Zhang et al., 2019).

Table 6. 11 Result of Strategy 3

Parameters	**Unit**	**MSW Input**	**Low-grade RDF**	**RDF**
HHV	MJ/kg	8.4 ± 0.1	5.8 ± 0.2	12.1 ± 0.8
LHV	MJ/kg	5.6 ± 0.1	3.0 ± 0.1	8.7 ± 0.8
MC	% wt. (ar.)	56 ± 0.9	61 ± 4	47 ± 3
Ash Content	% wt. (db.)	11 ± 0.2	18 ± 0.4	16 ± 0.4
S		0.22 ± 0.07	0.39 ± 0.02	0.31 ± 0.02
Cl		0.41 ± 0.07	0.52 ± 0.04	0.49 ± 0.02
C		-	37 ± 1	49 ± 1
H		-	6 ± 1	11 ± 1
N		-	1 ± 0.01	1 ± 0.01
O		-	37 ± 1	23 ± 1
Cd	mg/kg (db.)	-	10 ± 1	9 ± 1
Pb		-	14 ± 1	14 ± 1
Cr		-	13 ± 1	13 ± 1
Ni		-	15 ± 1	16 ± 1
Cu		-	35 ± 3	32 ± 4

Table 6.11 details the outcomes of strategy 3. The table showcases the transformation from MSW input into low-grade RDF and RDF, where the low-grade RDF's MC notably peaks at 61%, higher than the original MSW input, potentially due to moisture transfer during the separation process for RDF and low-grade RDF. This elevated moisture level suggested that the refinement process did not include a sufficient drying phase, leaving the RDF products with excessive dampness. The RDF's MC also remained relatively high, with an MC of 47%. An increase in ash content was observed during the conversion, hinting at an accumulation of non-combustible materials in the RDFs. Additionally, a modest rise in S and Cl was recorded post-conversion, along with an uptick in carbon content, especially in the low-grade RDF.

Due to high moisture, additional drying is recommended for low-grade RDF to improve its use as an AF. Strategy 4 incorporated a drying step to strategy 3's process by employing a belt dryer. Strategy 4 was conducted in 8 trials on January 2024, processing 100 Mg of MSW each. The belt dryer had a capacity of 3-4 Mg, processing about 55 Mg of MSW in 14-16 hours. A schematic of the workflow for strategy 4 is shown in Figure 6.10 below.

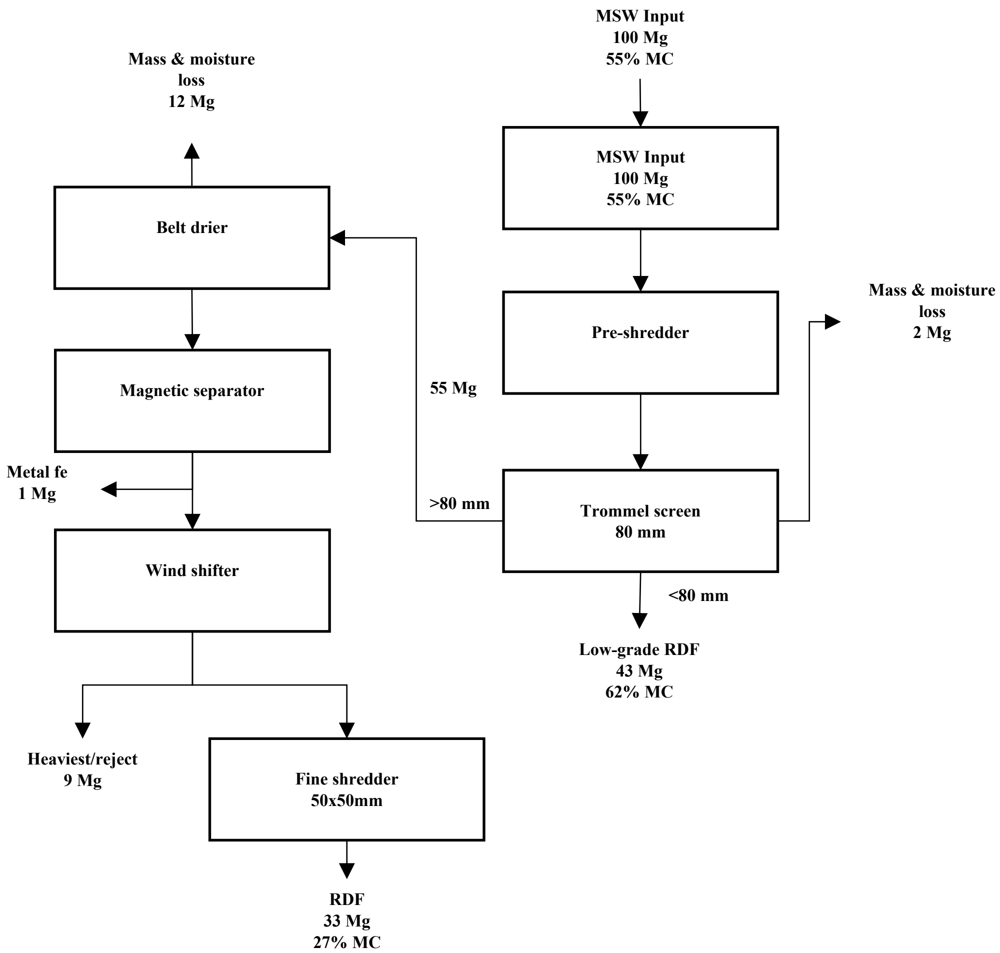

Figure 6. 10 Processes and Mass Flow in Strategy 4

Based on the results of the investigation, there is porosity on the surface of the belt dryer, with the blockage originating from the organic fraction. Therefore, it is recommended to properly sort the organic fraction to prevent this issue, which could lead to material jams and disrupt the drying process. There were also challenges with the trommel screen before the material entered the belt dryer. Although the belt dryer accelerated the drying process and enhanced the efficiency of MSW drying, in line with a review from Perazzini et al., (2016), further improvements were needed concerning capacity and achieving optimal moisture reduction.

Table 6. 12 Result of Strategy 4

Parameters	Unit	MSW Input	Belt Drier Output	Low-grade RDF	RDF
HHV	MJ/kg	8.4 ± 0.1	14.8 ± 0.3	5.7 ± 0.2	16.1 ± 0.9
LHV	MJ/kg	5.6 ± 0.1	11.7 ± 0.3	2.8 ± 0.1	13.1 ± 0.9
MC	% wt. (ar.)	55 ± 0.9	34 ± 2	62 ± 4	30 ± 1
Ash	% wt. (db.)	11 ± 2	16 ± 1	19 ± 0.36	17 ± 0.3
S		0.21 ± 0.05	0.49 ± 0.05	0.38 ± 0.04	0.41 ± 0.09
Cl		0.38 ± 0.06	0.79 ± 0.06	0.51 ± 0.05	0.59 ± 0.10
C		-	-	41 ± 1	53 ± 1
H		-	-	6 ± 1	11 ± 1
N		-	-	1 ± 0.01	1 ± 0.01
O		-	-	32 ± 1	17 ± 1
Cd	mg/kg (db.)	-	-	9 ± 1	10 ± 1
Pb		-	-	14 ± 1	15 ± 2
Cr		-	-	13 ± 1	12 ± 1
Ni		-	-	15 ± 1	14 ± 2
Cu		-	-	33 ± 2	33 ± 4

Table 6.12 outlines the results of strategy 4. The table shows that after processing through a belt dryer, the HHV of the output increased from 8.4 to 14.8 MJ/kg when compared to the MSW input, while the LHV rose from 5.6 to 11.7 MJ/kg, indicating enhanced energy potential. However, the MC of the belt drier output was 34%, a significant reduction from the 55% in the MSW input, but still presented challenges for low-grade RDF, which remained very wet with a 62% MC, likely because it did not undergo a drying phase. This indicated a need for further drying or treatment to optimise its use as a fuel source. RDF achieved better moisture reduction at 30%. Ash content moderately increased after drying, while S and Cl increased in concentration. As a supplement, Figure 6.11 on the following page displays examples of physical materials produced by all four pilot projects, which show similar results.

Figure 6. 11 Coarse Dried RDF, RDF, Low-Grade RDF, Heaviest/Reject (left to right)

A comparative assessment of mass balance was performed to determine the effectiveness of the processes. Figure 6.12 below illustrates the mass percentage distribution for various strategies. Strategy 1 had RDF at 33%, low-grade RDF at 24%, and mass loss at 34%. Strategy 2 was similar to strategy 1 but had slightly less low-grade RDF and greater mass loss. Strategy 3 stood out with increased percentages for RDF and low-grade RDF at 42% and 44%, respectively. Nevertheless, strategy 3 had a very low mass loss of 2% due to the absence of a drying process. Strategy 4 is akin to strategy 1 for RDF but had more low-grade RDF (43%) and rejects (9%), with a 14% mass loss. The yields of dry RDF materials were between 20 and 30%. These results correlate with other reports indicating that RDF output from MBT processes vary from 20-40% and depends on the MSW composition (Gadaleta et al., 2022). The pilot project's estimated RDF production was around 30% for RDF and 25% for low-grade RDF, targeting under 30% MC. This accounted for 55% of the MSW, equating to 7,900 metric Mg of RDF daily from 14,400 Mg of MSW.

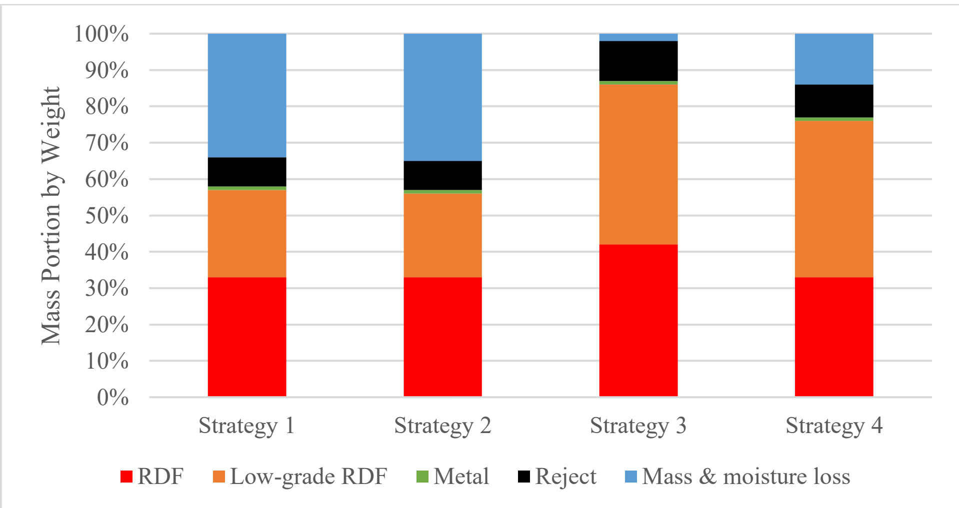

Figure 6. 12 Mass Balance Comparison Between the Strategies

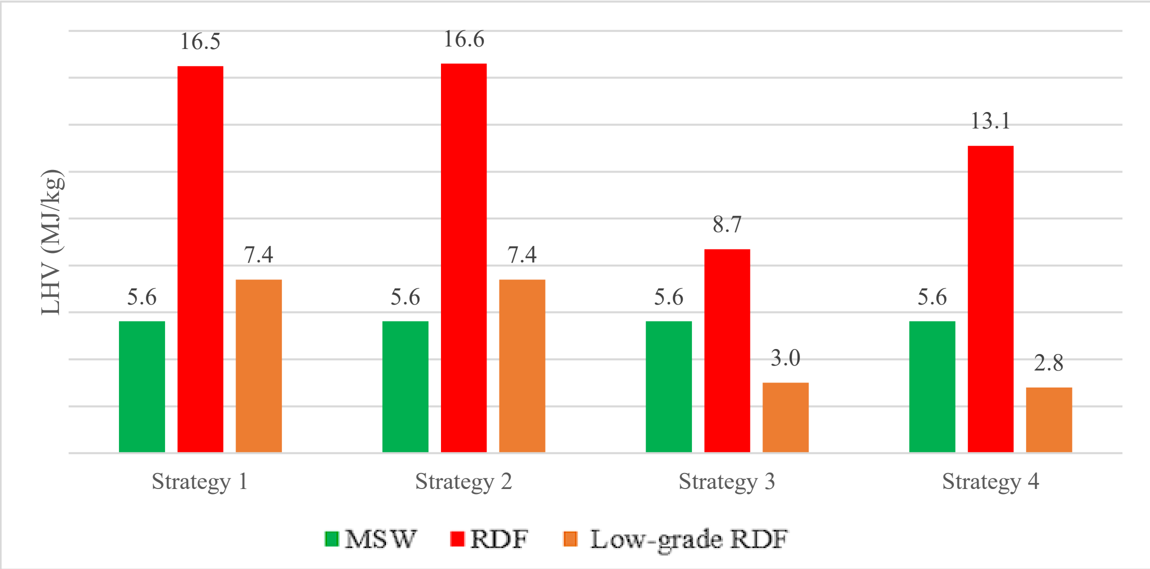

Figure 6. 13 Comparison of RDF's LHV Across Different Strategies

Figure 6.13 above compares the LHV of RDF across different strategies. The LHV of RDF output is higher compared to the LHV of MSW input across these strategies. The energy values of strategies 1 and 2 output were significantly higher than those of strategies 3 and 4. This is due to the drying process employed in the first two strategies, where the MSW was dried before the trommel separated it, enhancing the separation efficacy and yielding a higher-quality product. On the other hand, in strategies 3 and 4, the trommel worked with high moisture MSW, which led to suboptimal separation, resulting in a mixture of low-grade material in the high-grade fraction. The lack of a drying phase in strategies 3 and 4 also led to a considerably lower energy value in the low-grade RDF.

The RDF composition fractions from each strategy and the MSW were compared (Figure 6.14). The composition fractions of each RDF were based on a sample of 100 kg from each trial of all the strategies, with the sampling carried out before the fine shredding process. Notably, total organic content decreased RDF output considerably compared to the MSW average of 43%. RDF plastic content was doubled or more than doubled in all strategies compared to MSW, with the highest concentration in strategy 1 (53%). This indicated that the separation processes were highly effective in separating the organic and calory fractions. Like wood, paper content stayed relatively consistent across strategies and showed a notable increase compared to its initial MSW percentage. The relationship between MSW and RDF across these strategies shows that the processes involved in converting MSW to RDF are effective at enhancing the combustible fraction while eliminating or reducing non-combustible components aimed at optimising the fuel quality of the RDF. For the low-grade RDF fraction, this composition analysis was not performed due to the difficulty of identifying materials that have been stabilised with a size of less than 80 mm.

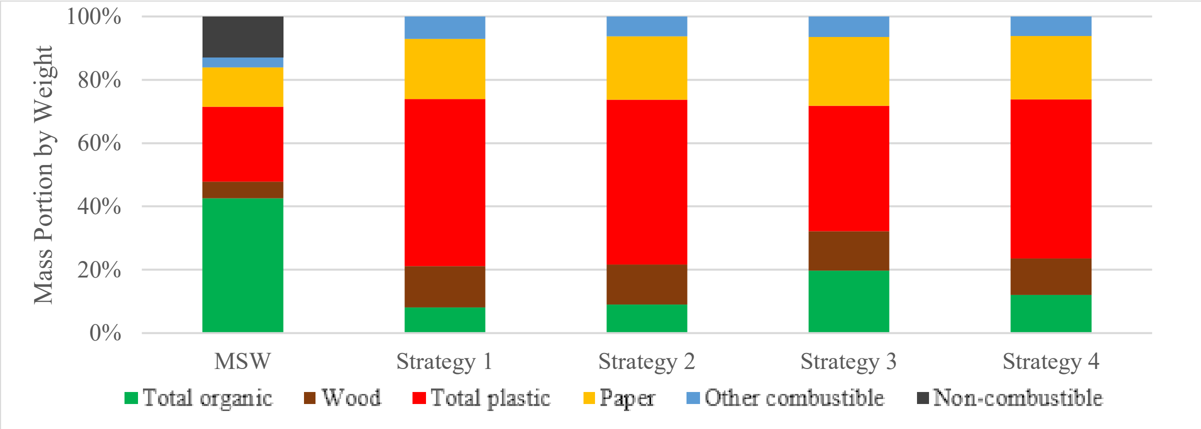

Figure 6. 14 Comparison of the Fractions Across All Strategies

6.3 RDF from Pilot Project Utilisation

In this section, the cement plant utilised the RDF products from the pilot projects as an AF despite not meeting the specifications. Before utilisation, it was necessary to assess the laboratory analysis results and compare them with the specifications adopted by the cement plant. As a supplement, specifications of RDF in Indonesia and Europe are also presented here. Additionally, it is necessary to summarise the quality of each strategy in a table and then compare them with the RDF specifications implemented at the cement plant (found in Chapter 4), Indonesia, and Europe.

According to the cement plant specification, the product output, RDF, and low-grade RDF were to meet the specification in the corresponding section. Based on the quality of MC, HHV, S, and Cl, the product output from all strategies was classified under spec 4. An exception was observed for the S content of strategy 4, which was 0.41%. Due to a deviation of 0.09%, the threshold was marginally exceeded.

As for the Indonesian RDF specification, strategy 3 did not meet the spec because its LHV 12.1 MJ/kg, which did not meet the minimum specification of 12.5 MJ/kg. According to EN 21640, all strategies fell into class 3, except for strategy 3, which was categorized under class 4. Meanwhile, based on the cement plant specification, the low-grade RDFs of all strategies were within spec 5. On the contrary, according to the specifications in Indonesia, the low-grade RDFs did not meet the requirements.

According to EN 21640, for strategies 1 and 2, low-grade RDF fell into Class 5 for LHV and Class 4 for Cl, while RDF fell into Class 3 for LHV and Class 4 for Cl. Strategy 3 produced low-grade RDF and RDF that met Class 5 for LHV and Cl. In contrast, strategy 4 produced low-grade RDF that met Class 5 for LHV and Cl, while RDF fell into Class 4 for LHV and Class 5 for Cl. All strategies met at least Class 5 for Cl, but those with lower LHV values were classified into lower classes. Table 6.13 further recapitulates the product output from each pilot project with typical RDF quality from other research.

Table 6. 13 Comparison of Pilot Project Outputs

Parameters	Unit	Strategy 1		Strategy 2		Strategy 3		Strategy 4		Typical RDF Quality
		Low-grade RDF	RDF	Low-grade RDF	RDF	Low-grade RDF	RDF	Low-grade RDF	RDF	
HHV	MJ/kg	9.5	19.3	9.5	19.6	5.8	12.1	5.7	16.1	16-32[4]
LHV	MJ/kg	7.4	16.5	7.4	16.6	3.0	8.7	2.8	13.1	12-30[1,3,8]
MC	% wt. (ar.)	30	27	30	27	61	47	62	30	12-49[8]
Ash	% wt. (db.)	29	18	30	19	18	16	19	17	6-20[4,8,9]
S		0.48	0.38	0.43	0.4	0.39	0.31	0.38	0.41	0.09-0.99[3,8,9]
Cl		0.67	0.62	0.66	0.67	0.52	0.49	0.51	0.59	0.2-1.0[4,8]
C		39	54	42.1	55	37	49	41	53	43-65[2,5,8,10]
H		6.3	9.7	6.2	10	6	11	6	11	6-11[6,8,9]
N		0.7	0.6	0.7	0.55	0.75	0.5	0.8	0.6	0.3-1.0[3,8]
O		24	17	20	14	37	23	32	17	14-37[5,9]
Cd	mg/kg (db.)	9	10	9	17	10	9	9	10	1-22[2,3,4,7]
Pb		13	13	18	16	14	14	14	15	7-91[2,3,7]
Cr		10	13	11	12	13	13	13	12	2-70[3,4,10]
Ni		20	21	18	20	15	16	15	14	2-64[2,3,4]
Cu		34	28	28	32	35	32	33	33	23-115[2,3,10]

([1]Consonni et al., 2005; [2]Crujeira et al., 2005; [3]Gendebien et al., 2003; [4]Hemidat et al., 2019; [5]Nowak, 2023; [6]Paszkowski et al., 2020; [7]Sanjel, 2012; [8]Sarquah et al., 2023; [9]Topal, 2018; [10]Zhao et al., 2016)

Compared to other research, as shown in Table 6.13, the most distinct differentiating factor in this study is the presence of low-grade RDF, with the primary divergent parameters being its lower LHV and higher ash content. This indicates that the low-grade RDF produced in this context may require additional processing to increase its energy recovery potential. Nevertheless, the cement plant was flexible in terms of quality due to its robust combustion system. This enables the plant to use lower-quality fuels effectively while maintaining efficient operations.

Once the specifications of the RDF products had been examined, they were fed into the calciner. The RDFs from strategies 1-4 and low-grade RDFs from strategies 1 and 2 could be directly fed into the calciner. However, the low-grade RDFs from strategies 3 and 4 needed to be mixed with sawdust because of the MCs that were higher than 60%. The established mixing ratio was 1:10, with 1 part being the low-grade RDF and 10 parts sawdust. This mixing resulted in a final MC of about 30%.

Table 6. 14 Utilisation of the RDF Products from Pilot Projects

Parameter	Unit	Strategy 1		Strategy 2		Strategy 3		Strategy 4	
		RDF	Low-grade RDF	RDF	Low - grade RDF	RDF	Low - grade RDF	RDF	Low-grade RDF
Total Mass	Mg	332	241	332	233	423	441	266	345
Moisture	% wt. (ar.)	27	30	27	30	47	61	30	62
LHV	MJ/kg	16.5	7.4	16.6	7.4	8.7	3.0	13.1	2.8
Net energy generated	GJ	5480	1779	5527	1729	3663	1306	3478	979
C	% wt. (db.)	54	39	55	42	49	37	53	41
C	% wt. (ar.)	39	27	40	29	26	14	37	16
Biomass	% wt. (db.)	40	64	42	64	55	64	44	64
CO_2 emission factor	Kg CO_2/GJ	52.4	49.2	51.7	52.9	50.0	64.8	58.7	73.1
CO_2 emission reduction	Mg	248	86	254	77	174	43	135	24

Table 6.14 showcases the computed values of energy generation and the prospective CO_2 emissions mitigation derived from employing RDFs produced by the pilot projects. The net energy generated was derived by multiplying the LHV by the amount of RDF produced. The total energy generated across all strategies was 23,941 GJ. The biomass content of RDF was assumed to be based on the sum of the fractions of organic (garden), organic (leftover), wood, 2D and 3D plastics, paper, and cardboard for each strategy. The biomass content was derived from the same fractions in MSW sized less than 80 mm for low-grade RDF, taken from the particle size distribution analysis. For comparison, a biomass content test was also conducted on a single RDF sample from Jakarta, using the determination of the biomass content in solid recovered fuels, i.e., the 14C content method, EN ISO 21644:2021 (CEN, 2021b), where the biomass content was found to be 48.7%. This result aligns closely with the average result of approximately 45% calculated for the pilot project's RDF output product. Obtaining the biomass content value from the biomass fraction is a more practical approach compared to the 14C test. The calculation of the CO_2 emission factor derived from the carbon content of each product divided by its LHV, then multiplied by the non-biomass fraction. The average emissions from this pilot project were higher than those reported by Lechtenberg & Partner, (2008) at 27 Kg CO_2/GJ. This occurred because the RDFs produced in the pilot project had higher MC. The CO_2 emission reduction was calculated by subtracting the coal CO_2 emission factor of 97.6 Kg CO_2/GJ (Juhrich, 2022) and each RDF output product's CO_2 emission factor. All products' total potential CO_2 reduction was estimated to be 1042 Mg.

7. Modelling RDF Production and Utilisation in The Cement Plant

This section presents a modelling analysis featuring four RDF Production models. To simplify, the models are referred to as RDFP-1, RDFP-2, RDFP-3, and RDFP-4, with the 'P' for 'production'. Each model was carefully crafted by leveraging data from MSW characterisation studies, primarily focusing on analysing MSW fraction results and incorporating a separation process efficiency factor for mechanisms like trommels and wind shifters, which was set at 75%. Consequently, the output product of RDF was expected to decrease compared to the pilot project results and align with the designated design criteria outlined below.

- Operation duration = 20 years, based on the Public-Private Partnership (PPP) mechanism
- MSW input = 182,500 Mg/year, equating to 500 Mg/day or 28 Mg/hour
- MSW input moisture = 55% wt. (ar.)
- MSW input HHV = 8.5 MJ/kg
- MSW input density = 0.35 Mg/m^3
- Working days = 365 days/year
- Working hours = 18 hours/day in 3 shifts. Equating to 6,300 hour/year
- Number of workers = 61 persons
- Interest rate = 2.89% pa. (IFC, 2022)
- Debt period = 5 years
- Tipping fee increment = 5% pa.
- Inflation rate = 6% pa. (BI, 2023)
- Wage increment = 2% pa. (BPS, 2023a)
- Asset insurance = 0.1965% pa. (Kemenkeu, 2020)
- Income tax = 22% Law Number 7 of 2021 on the Harmonization of Tax Regulations Indonesia (BPKRI, 2024)
- Building maintenance = 2% of Capex pa. (LSI, 2021)
- Equipment maintenance = 5-10% of Capex pa. (LSI, 2021)
- Carbon price = €35/Mg assumption. The price on April 2024 was €70/Mg (EC, 2024; Trading Economics, 2024)
- Tipping fee = As per Presidential Regulation No. 35 of 2018, the maximum tipping fee for WtE and thermal treatment was €29.8/Mg of MSW (Perpres, 2018). The rate applied in the models was €22/Mg of MSW.

- Recycled metal sales = A maximum of €208.3/Mg, adopted according to Governor Regulation No. 46 of 2023 on MSW Management Tariff (DKI Jakarta, 2023).
- Currency rate = The exchange rate was IDR 16,800 to €1, and $1 was equivalent to €0.93.
- Pre-operation Cost = Accrued as part of the Capex, including EIA, licenses, and consultancy, amounting to €84,000 (LSI, 2021).

These criteria ensured that the models were theoretically robust and practically viable. The targeted outputs were evaluated based on the pricing proposal, several technical aspects, RDF output quality, potential energy, CO_2 benefits for the cement plant, and an economic feasibility study (Mukherjee et al., 2019).

The calculation of the proposed RDF price aims to be fair and fulfill the concept that the cement plant values fuel based on the number of calories it contains. Therefore, the RDF price calculation was benchmarked based on the coal price index. The pricing proposal adhered to the domestic market obligation (DMO) coal price in Indonesia, set at $90/Mg (ESDM, 2022), with an additional freight cost to the cement plants averaging €11/Mg. Therefore, coal's delivered duty paid (DDP) price at the cement plant was approximately €94.7/Mg. This DMO price was established for coal with an HHV of 6322 Kcal/kg or 26.5 MJ/kg with an MC of 8% or an LHV of 25.3 MJ/kg. This price was converted into a fuel price in €/GJ units based on the LHV, also called the net heat price, which amounted to €3.7/GJ. Figure 7.1 illustrates the suggested pricing for RDF.

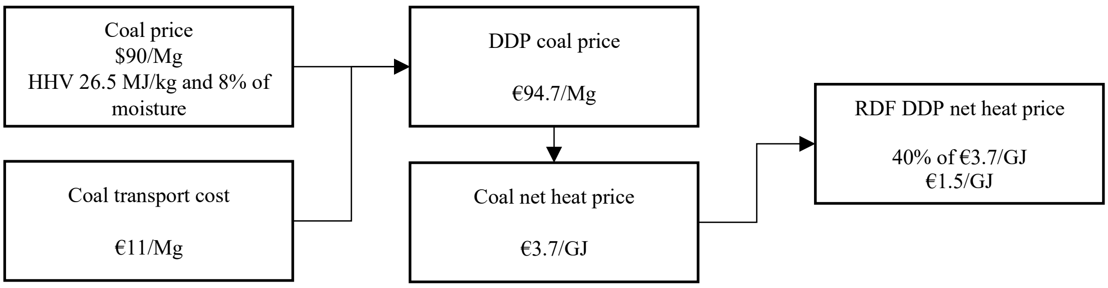

Figure 7. 1 RDF Pricing Proposal

The price for RDF or other AFs could be applied and was approximately 40% of the coal net heat price. This 40% reflects RDF's lower combustion efficiency compared to coal. Substituting coal with RDF in the combustion process of cement production is a viable option. However, this substitution necessitates a higher specific energy consumption and leads to a diminished production capacity due to RDF's lower combustion efficiency and density in comparison with coal (Kahawalage et al., 2017). Consequently, the DDP net heat price benchmark for RDF and low-grade RDF was set at €1.5/GJ. The RDF price in this study ranged from €8-25/Mg, while in Europe, the price of RDF ranged from €20-70/Mg (Srivastava, 2021)

In selecting the site for the RDF production plant, RDFP-1, RDFP-2, and RDFP-4 were integrated into a single production entity to streamline sorting, drying, and refining processes. These were located within the respective city, owned by the city government, and outside the cement plant. For RDFP-3, the government would allocate land within the city for the sorting and refining processes of MSW, but not for the drying process. Instead, additional land was provided at the cement plant for drying, which employed box drying with hot gas. This created a dual-location layout: pre-drying occurred outside the cement plant and drying process within the cement plant itself. As a note, the land provided for these investments was already available from the local government and the cement plant. In this modelling, the PPP mechanism has been adopted. According to the World Bank and Indonesian Presidential Regulation of Indonesia No. 35, 2015, PPP is a collaborative framework between the public and private sectors where expertise and resources from both sectors are combined to design, finance, construct, and operate a project (BPKRI, 2024; World Bank, 2023a). In relation to the RDF plant, the central government represented the public party while Indocement represented the private party. The implementation process is depicted in Figure 7.2.

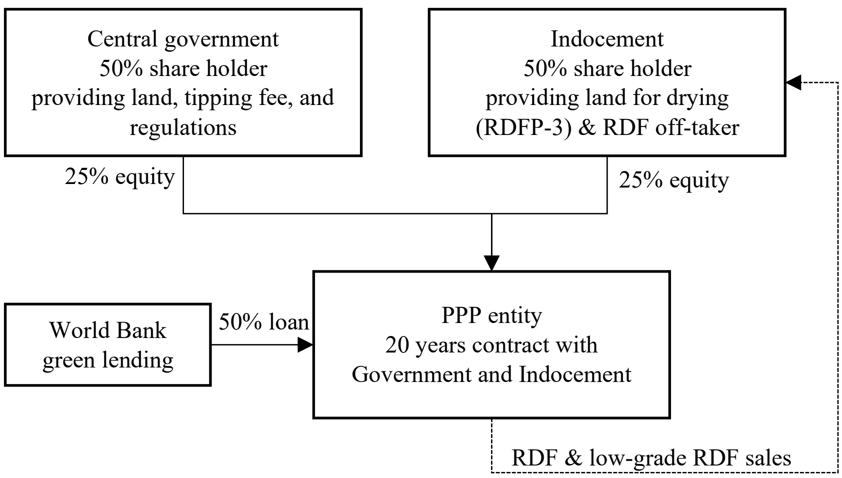

Figure 7. 2 PPP Mechanism

The central government holds a 50% stake, playing a role in providing land, tipping fees, and supportive regulations, including carbon sales and accommodating rejected material at landfills. Meanwhile, Indocement holds a 50% stake and is responsible for the drying process, as well as an off-taker of RDF products, including low-grade RDF. This PPP entity involves a contract between the central government and Indocement for 20 years. The PPP is supported by a green loan from the World Bank amounting to 50% equity, with the remaining equity being divided equally between the central government and Indocement.

The quality modelling focuses on parameters such as MC, HHV, LHV, ash, S, and Cl, which were calculated using the weighted average of the MSW fractions. The carbon content of RDF was also used to calculate CO_2 emissions for assessing financial performance. The payback period was determined using the subtraction method in the modelling. This approach involved subtracting annual cash flows from the initial investment, which was 50% of the equity amount, consecutively until the investment was recovered. The resulting period was then calculated by dividing the total amount to be recovered by the annual cash flows. This method proves to be more effective when cash flows vary yearly (Clark et al., 1984).

7.1 RDFP-1: Bio-drying with Membrane

The RDFP-1 followed strategy 1, in which the drying process utilised membrane bio-drying with aeration for 16 days in an open space. The process flow for RDFP-1 is shown in Figure 7.3.

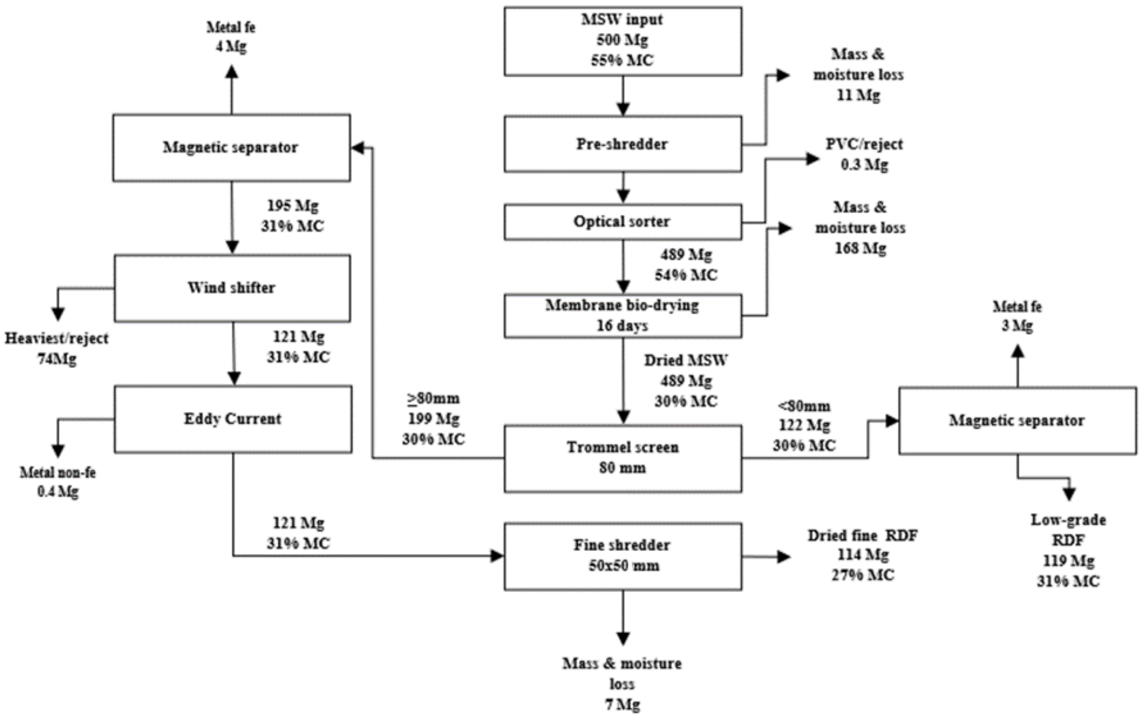

Figure 7. 3 Modelling Result of RDFP-1

Next, Table 7.1 provides a summary of the RDFP-1 model, offering an overview of key analyses such as quality and CO_2 emission savings. The table portrays a comprehensive snapshot of 500 Mg of MSW per day's processing and transformation per day through various fractions to generate AF for cement plants. The breakdown of the output indicated that 114 Mg of RDF, 119 Mg of low-grade RDF, and 74 Mg of rejected material were produced daily, alongside a minor yield of metal at 8 Mg and a notable amount designated as moisture and mass loss at 185 Mg. Each fraction constituted a percentage of the total mass, with RDF and low-grade RDF each making up close to a quarter of the MSW, rejected material 15%, and metal a mere 2%. The collected output earmarked as AF for the cement plant aggregated to 233 Mg, representing 47% of the processed MSW.

Table 7. 1 Summary of the RDFP-1 Model

Parameter	**Unit**	**MSW Input**	**Output**					
			RDF	**Low-grade RDF**	**Rejected material**	**Metal**	**Moisture and mass Loss**	**Total AF for the cement plant**
Mass	Mg/day	500	114	119	74	8	185	233
Mass	%	100%	23	24	15	2	37	47
MC	% wt. (ar.)	55	27	31	-	-	-	29
LHV	MJ/kg	5.6	16.1	7.8	-	-	-	11.9
Net heat	GJ/day	2,775	1,844	920	-	-	-	2,764
Ash	% wt. (db.)	11	16	30	-	-	-	23
S	% wt. (db.)	0.24	0.43	0.40	-	-	-	0.42
Cl	% wt. (db.)	0.36	0.69	0.59	-	-	-	0.64
C	% wt. (db.)	47	54	38	-	-	-	46
C	% wt. (ar.)	21	39	26	-	-	-	33
Biomass content	%	60	55	47	-	-	-	51
CO_2 emission factor	Kg CO_2/GJ	55.2	40.6	66.6	-	-	-	53.9
CO_2 emission factor difference compared to coal (97.6)	Kg CO_2/GJ	42.4	57.0	31.0	-	-	-	43.7
CO_2 savings	Mg/day		105	28	-	-	-	134

Regarding energy content, the LHV for the MSW input was 5.6 MJ/kg. Following processing the MSW to RDF, the LHV almost tripled to 16.1 MJ/kg, signifying a higher energy density suitable for efficient combustion. Although lower than RDF, the low-grade RDF's LHV of 7.8 MJ/kg still offered substantial energy recovery possibilities. Based on the net heat price, RDF and low-grade RDF had €24.06/Mg and €11.56/Mg sales, respectively. The total net heat available per day from the MSW amounted to 2,775 GJ, with the RDF contributing a majority of the total net heat at 1,844 GJ. The collective AF for the cement plant closely matched the value with 2,764 GJ/day. Ash, S, and Cl contents were quantified to assess potential emissions during combustion. RDF showcased the highest figures of the three parameters, significantly exceeding the MSW input, notably with Cl at 0.69% on a dry basis. Carbon content in RDF was high at 54% and included biomass content, which reflects the potential for net-zero emissions or carbon neutrality. The CO_2 emission factor decreased substantially from 55.2 Kg CO_2/GJ in MSW to as low as 40.6 Kg CO_2/GJ for RDF. Meanwhile, the low-grade RDF had the highest CO_2 emission factor with a value of 66.6 Kg CO_2/GJ. The total CO_2 savings potential was 134 Mg/day, consisting of 105 and 28 Mg/day for RDF and low-grade RDF, respectively.

There is a breakdown of the capital expenditure (Capex) for RDFP-1, starting with the pre-operation costs amounting to €84,000, followed by further details for equipment and building-civil works expenses, which can be observed in Table 7.2 below.

Table 7. 2 Capex for Equipment in RDFP-1

No	Equipment	Lifetime	Total Capacity	Total Unit	Total Cost Includes VAT
		Year	Mg/day		€
1	Hopper, dosing & feeder	15	600	1 set	230,714
2	Truck scale	15	600	2	138,429
3	Pre-shredder	10	600	2	1,195,100
4	Optical sorter	10	600	1	357,143
5	Membrane bio-drying	10	Lump sum	1	2,500,000
6	Trommel	10	600	2	1,095,893
7	Magnetic separator	10	600	4	403,750
8	Wind-shifter	10	300	1	314,925
9	Eddy current	10	270	1	288,393
10	High speed fine shredder	10	270	1	1,038,214
11	Conveyor system	8	600	1 set	531,358
12	Loader	8	600	6	519,107
13	Dump truck	8	600	3	155,732
14	Crane	8	600	1	95,170
15	Power transmission	15	-	1 set	213,411
16	Electric & control system	15	-	1 set	165,194
17	Equipment substructure	15	-	1 set	273,973
18	Pipe & blower system	15	-	1 set	173,469
19	Laboratory	15	-	1 set	144,196
20	Instrument	15	-	1 set	144,196
21	Safety & monitoring	15	-	1 set	173,036
	Total				10,151,404

Table 7.3 provides a detailed breakdown of the Capex dedicated to the building construction and civil work activities for the development of the RDF production plant.

Table 7. 3 Capex for Building-Civil Works RDFP-1

No	Building/Civil Works	Area	Lifetime	Total Cost Includes VAT
		m^2	years	€
1	Treatment area	2,500	20	1,190,476
2	RDF storage	2,000	20	833,333
3	Security	21	20	10,000
4	Gate	56	20	26,667
5	Office & Laboratory	500	20	238,095
6	Workshop	500	20	238,095
7	Safety & fire	300	20	142,857
8	Housing	100	20	47,619
9	Central control room	150	20	71,429
10	Utility	500	20	238,095
11	Electrical	700	20	333,333
12	Truck scale area	350	20	166,667
13	Washing area	240	20	114,286
14	Road, drainage, & landscape	2,375	20	282,750
15	Bio-drying area (36 lanes,4.5mx65m)	18,662	20	5,554,286
16	Land preparation		20	237,200
	Total	**28,955**		9,725,188

For RDFP-1, an estimated area of 2.9 hectares of land was required. Furthermore, the total Capex for processing 500 Mg/day of MSW, which amounted to 182,500 Mg/year, was estimated to be around €19.9 million. Table 7.4 below estimates the Capex over a period of up to 20 years, with particular amounts allocated in certain years corresponding to the lifespan of the equipment.

Table 7. 4 Estimated Total Capital Expenditure Over 20 Years for RDFP-1

Item	Unit	Initial Year	Year 9	Year 11	Year 16	Total
Pre-operation cost	€	83,333	-	-	-	83,333
Equipment	€	10,151,404	2,074,182	12,951,903	3,305,930	28,483,419
Building-civil works	€	9,725,188	-	-	-	9,725,188
Total	€	19,959,925	2,074,182	12,951,903	3,305,930	38,291,940

Table 7.5 on the following page summarises the projected revenue for the first year and the average annual revenue over 20 years of operation for the RDFP-1 model. This summary provides a financial estimate derived from the fully functional model, generating income as presented in Table 7.5. The total annual revenue thus could reach an estimated €7.8 million, which is expected to increase over time due to inflation and favourable gate fee adjustments. Therefore, if averaged over 20 years, the revenue was estimated to be €10.8 million.

Table 7. 5 Revenue of RDFP-1

Item	Unit Price Year 1	Quantity	Total Revenue Year 1	Average Revenue 20 Years
	€/Mg	Mg/year	€	€
Tipping fee of MSW	22.0	182,500	4,019,345	6,645,174
RDF	24.1	41,683	1,002,713	1,002,713
Low-grade RDF	11.6	43,280	500,379	500,379
Metal	208.3	2,838	591,182	977,399
Carbon sales by RDF	35.0	38,378	1,343,242	1,343,242
Carbon sales by low-grade RDF	35.0	10,397	363,892	363,892
Total	24.5	319,075	7,820,752	10,832,798

Next, Table 7.6 displays the results of the calculations for cost and net income, as shown below. After accounting for all expenses, the net income for the first year was €164,637. However, when the expenses were spread over two decades, the annual net income average substantially increased to €1.5 million. Based on financial performance calculations, by subtracting the net income from the total equity until a positive balance is obtained, the payback period for this model was determined to be 18.8 years, with an ROI over 20 years of 53%.

Table 7. 6 Cost and Net Income of RDFP-1

Cost	Unit	Year 1	20 Years Average
Variable cost			
RDF transportation to the cement plant	€	310,139	570,432
Low-grade RDF transportation to the cement plant	€	257,616	473,828
Reject transportation	€	270,253	497,070
Maintenance: building-civil works	€	194,504	357,747
Maintenance: equipment	€	1,015,140	1,867,127
Electricity	€	517,423	951,685
Fuel	€	718,007	1,320,616
Total variable cost	€	3,283,081	6,038,505
Fix cost			
Labour	€	639,167	776,503
Equipment depreciation	€	980,549	980,549
Building-civil works depreciation	€	486,259	486,259
Insurance	€	39,221	39,221
Total fix cost	€	2,145,196	2,282,533
Total Cost	€	5,428,278	8,321,038
Debt bearing	€	2,181,400	109,070
Income before tax (revenue-total cost)	€	211,074	1,966,410
Tax income	€	46,436	432,610
Net income	**€**	**164,637**	**1,533,800**
Net income	€/Mg of MSW	1	8
Opex	**€**	**3,922,248**	**6,967,259**
Opex	€/Mg of MSW	21	38
Payback period	**Year**	**18.8**	
ROI	**%**		**53**

Figure 7.4 provides a summary of the financial model. This model includes key financial metrics such as Capex, payback, ROI, revenue, and costs. These components are essential for evaluating the overall financial performance and feasibility of the project.

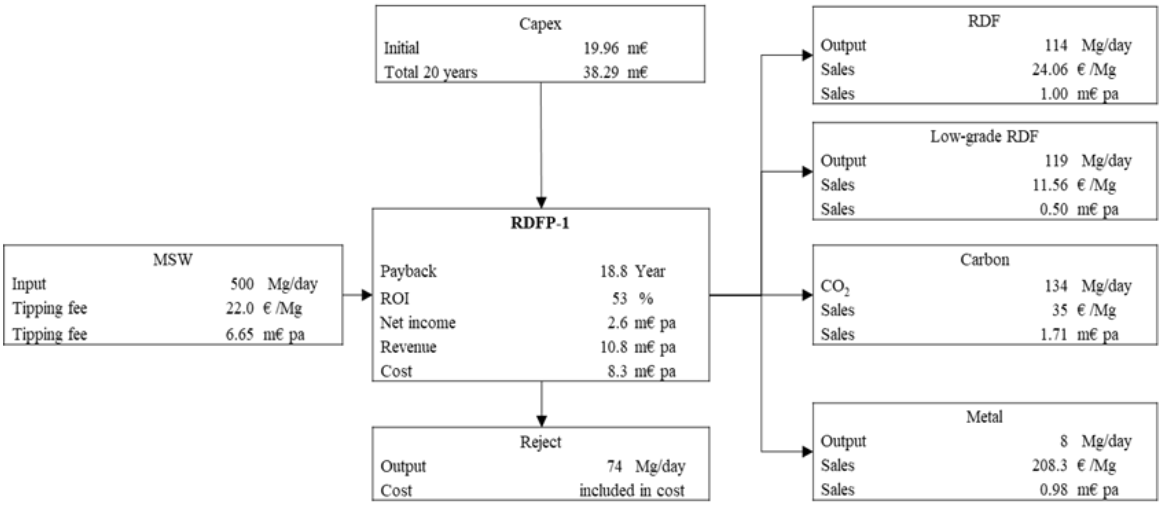

Figure 7. 4 Summary of RDFP-1 Financial Analysis Over 20 Years

7.2 RDFP-2: Bio drying with Turner and Transparent Roof

The processes in RDFP-2 were similar to RDFP-1 but with a shorter 13-day bio-drying period and sunlight exposure. The process was expected to produce similar outputs using the same MSW characterisation result. Figure 7.5 below illustrates the flow process for RDFP-2.

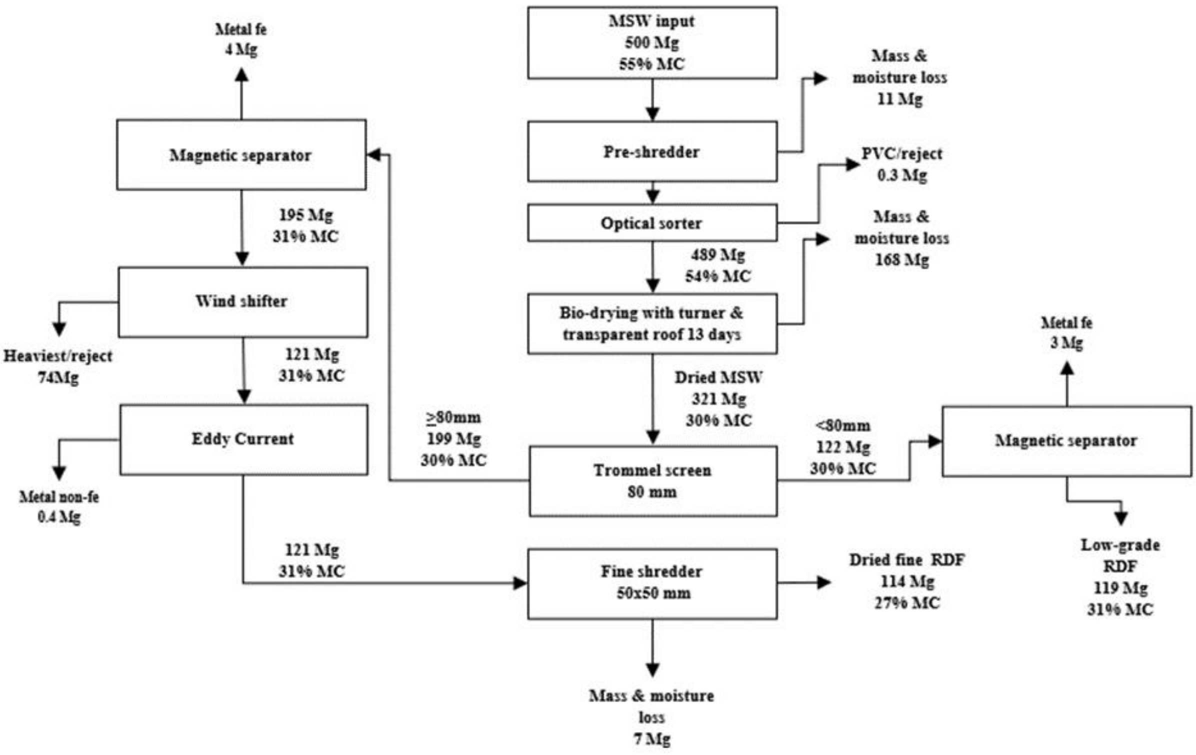

Figure 7. 5 Modelling Result of RDFP-2

Table 7.7 below provides a summary of the RDF-2 model, offering an overview of key analyses such as material quality and CO_2 emission savings. RDF's output and energy values represented a significant portion of the processing capacity, where RDF made up 23% of the daily processed mass and yielded a net heat of 1,844 GJ per day due to its high LHV. Meanwhile, low-grade RDF accounted for 24% of the daily process, with a lower LHV of 7.8 MJ/kg, contributing 920 GJ to the daily net heat output. Collectively, these materials provided close to half of the processed mass with an average LHV of 11.9 MJ/kg, culminating in a considerable daily net heat generation of 2,764 MJ. The combination of high and low-grade RDFs created a robust energy recovery scenario, enhancing the RDF production plant's efficiency. The CO_2 emission factor for RDF and low-grade RDF was considerably lower than that of coal, leading to significant CO_2 savings of 134 Mg/day for the cement plant. The results were similar to those of RDFP-1 because they are based on the same MSW fraction. The only difference was in the drying method used. The RDFP-2 model implemented an alternative drying process, resulting in minor variations in the final RDF product.

Table 7. 7 Summary of the RDFP-2 Model

Parameter	**Unit**	**MSW Input**	**Output**					
			RDF	**Low-grade RDF**	**Rejected material**	**Metal**	**Moisture and mass loss**	**Total AF for the cement plant**
Mass	Mg/day	500	114	119	74	8	185	233
Mass	%	100	23	24	15	2	37	47
MC	% wt. (ar.)	55	27	31	-	-	-	29
LHV	MJ/kg	5.6	16.1	7.8	-	-	-	11.9
Net heat	GJ/day	2,775	1,844	920	-	-	-	2,764
Ash	% wt. (db.)	11	16	30	-	-	-	23
S	% wt. (db.)	0.24	0.43	0.40	-	-	-	0.42
Cl	% wt. (db.)	0.36	0.69	0.59	-	-	-	0.64
C	% wt. (db.)	47	54	38	-	-	-	46
C	% wt. (ar.)	21	39	26	-	-	-	33
Biomass content	%	60	55	47	-	-	-	51
CO_2 emission Factor	Kg CO_2/GJ	55.2	40.6	66.6	-	-	-	53.9
CO_2 emission factor difference compared to coal (97.6)	Kg CO_2/GJ	42.4	57.0	31.0	-	-	-	43.7
CO_2 savings	Mg/day		105	28	-	-	-	134

Subsequently, a detailed Capex outline for RDFP-2 is presented in Table 7.8, commencing with pre-operation costs of €84,000. The table also provides detailed figures for equipment and building-civil works costs, which are listed on the following page.

Table 7. 8 Capex for Equipment in RDFP-2

No	Equipment	Lifetime	Total Capacity	Total Unit	Total Cost Includes VAT
		Year	Mg/Day		€
1	Hopper, dosing and feeder	15	600	1 set	230,714
2	Truck scale	15	600	2	138,429
3	Pre-shredder	10	600	2	1,195,100
4	Optical sorter	10	600	1	357,143
5	Turning machine	8	600	3	1,714,286
6	Trommel	10	600	2	1,095,893
7	Magnetic separator	10	600	4	403,750
8	Wind shifter	10	300	1	314,925
9	Eddy current	10	270	1	288,393
10	High speed fine shredder	10	270	1	1,038,214
11	Conveyor system	8	600	1 set	531,358
12	Loader	8	600	2	173,036
13	Dump truck	8	600	3	155,732
14	Crane	8	600	1	95,170
15	Power transmission	15	-	1 set	213,411
16	Electric and control system include bio-dying	15	-	1 set	165,194
17	Equipment substructure	15	-	1 set	273,973
18	Pipe and blower system	15	-	1 set	173,469
19	Laboratory	15	-	1 set	144,196
20	Instrument	15	-	1 set	144,196
21	Safety and monitoring	15	-	1 set	173,036
	Total				9,019,618

What set RDFP-2 apart from RDFP-1 equipment-wise was the inclusion of a turner machine in RDFP-2's configuration while it operated without a membrane system. Consequently, this necessitated extra capital expenditure for constructing a storage facility topped with a transparent roof to accommodate RDFP-2's modified operational needs. This infrastructural modification was tailored to complement the processing technique to RDFP-2, ensuring optimal land use for MBT.

Table 7.9 on the following page provides a detailed summary of the capital expenditures associated with constructing the new storage facility. This includes the costs for the necessary civil work. The table offers a clear financial overview of the project's infrastructure requirements.

Table 7. 9 Capex for Building-Civil Works in RDFP-2

No	Building/Civil Works	Area	Lifetime	Total Cost Includes VAT
		m^2	years	€
1	Treatment area	2,500	20	1,190,476
2	RDF storage	2,000	20	833,333
3	Security	21	20	10,000
4	Gate	56	20	26,667
5	Office and Laboratory	500	20	238,095
6	Workshop	500	20	238,095
7	Safety & fire	300	20	142,857
8	Housing	100	20	47,619
9	Central control room	150	20	71,429
10	Utility	500	20	238,095
11	Electrical	700	20	333,333
12	Truck scale area	350	20	166,667
13	Washing area	240	20	114,286
14	Road, drainage, and landscape	2,375	20	282,750
16	Bio-drying area (30 lanes, 4.5 x 65 m) with transparent roof	15,552	20	6,480,000
18	Land preparation		20	260,343
	Total	**25,844**		10,674,045

The RDFP-2 required about 2.6 hectares of land. The Capex for processing 500 Mg of MSW per day (182,500 Mg/year) was estimated at €20.2 million. The Capex is detailed in Table 7.10 over a period of 20 years, with specific years indicated for increased Capex corresponding to the lifespans of the equipment.

Table 7. 10 Estimated Total Capital Expenditure Over 20 Years for RDFP-2

Item	Unit	Initial Year	Year 9	Year 11	Year 16	Total
Pre-operation cost	€	83,333	-	-	-	83,333
Equipment	€	9,415,618	4,254,907	7,765,608	2,426,787	23,862,921
Building-civil works	€	10,674,045	-	-	-	10,674,045
Total	€	20,172,996	4,254,907	7,765,608	2,426,787	34,620,299

Next, Table 7.11 provides forecasts of the expected revenue for the initial year and a 20-year average from operating the RDFP-2 model. This financial projection was based on the assumption that the model is fully operational and generating revenue. The table shows RDFP-2's revenue, with the tipping fee for MSW at €22.0/Mg and 182,500 Mg/year, totalling €4,019,345 for year 1. RDF sales were stable at €24.1/Mg for 41,683 Mg/year, yielding €1,002,713 annually. Over 20 years, RDF's average revenue is consistent at €1,002,713. Other sales, including the sales of low-grade RDF, metal, and carbon, contribute to the revenue. Year

1's total revenue was €7,820,752, with a 20-year average of €10,832,798. Carbon sales accounted for 22% of revenue in both RDFP-1 and RDFP-2.

Table 7. 11 Revenue of RDFP-2

Item	Unit Price Year 1	Quantity	Total Revenue Year 1	Average Revenue 20 Years
	€/Mg	Mg/year	€	€
Tipping fee of MSW	22.0	182,500	4,019,345	6,645,174
RDF	24.1	41,683	1,002,713	1,002,713
Low-grade RDF	11.6	43,280	500,379	500,379
Metal	208.3	2,838	591,182	977,399
Carbon sales by RDF	35.0	38,378	1,343,242	1,343,242
Carbon sales by Low-grade RDF	35.0	10,397	363,892	363,892
Total	24.5	319,075	7,820,752	10,832,798

Table 7.12 is presented below, detailing the costs and net income. The table also highlights the financial outcomes of the RDFP-2 operation, showing that the initial year's operating expenses were set at €3,834,961, or €21 per Mg of MSW, which escalated over two decades to a 20-year average of 38 €/Mg. The first year sees a net income of €272,469— effectively €1 per Mg of MSW—with a remarkable increase to a 20-year average of 8 €/Mg. The operation anticipates a payoff time of 15.9 years, with a consistent upward trajectory in profitability, evidenced by a return on investment at 50%. This reflects efficient MSW processing and the effectiveness of the operation's financial strategy over the long term.

Table 7. 12 Cost and Net Income of RDFP-2

Cost	Unit	Year 1	20 Years Average
Variable cost			
RDF transportation to the cement plant	€	310,139	570,432
Low-grade RDF transportation to the cement plant	€	257,616	473,828
Reject transportation	€	270,253	497,070
Maintenance: building-civil works	€	213,481	392,651
Maintenance: equipment	€	941,562	1,731,795
Electricity	€	517,423	951,685
Fuel	€	732,086	1,346,510
Total variable cost	€	3,242,559	5,963,972
Fix cost			
Labour	€	639,167	951,658
Equipment depreciation	€	901,576	901,576
Building-civil works depreciation	€	533,702	533,702
Insurance	€	39,640	39,640
Total fix cost	€	2,114,085	2,426,576
Total Cost	€	5,356,643	8,390,548
Debt bearing	€	2,204,590	110,229
Income before tax (revenue-total cost)	€	259,519	1,891,103
Tax income	€	57,094	416,043
Net income	**€**	**202,424**	**1,475,061**
Net income	€/Mg of MSW	1	8
Opex	**€**	**3,881,725**	**6,915,630**
Opex	€/Mg of MSW	21	38
Payback period	**Year**	**15.9**	
ROI	**%**		**50**

Figure 7.6 below offers a summary of the financial model for RDFP-2. This model highlights key financial components, including Capex, payback, ROI, revenue, and costs. These components are crucial for assessing the project's overall financial performance and feasibility.

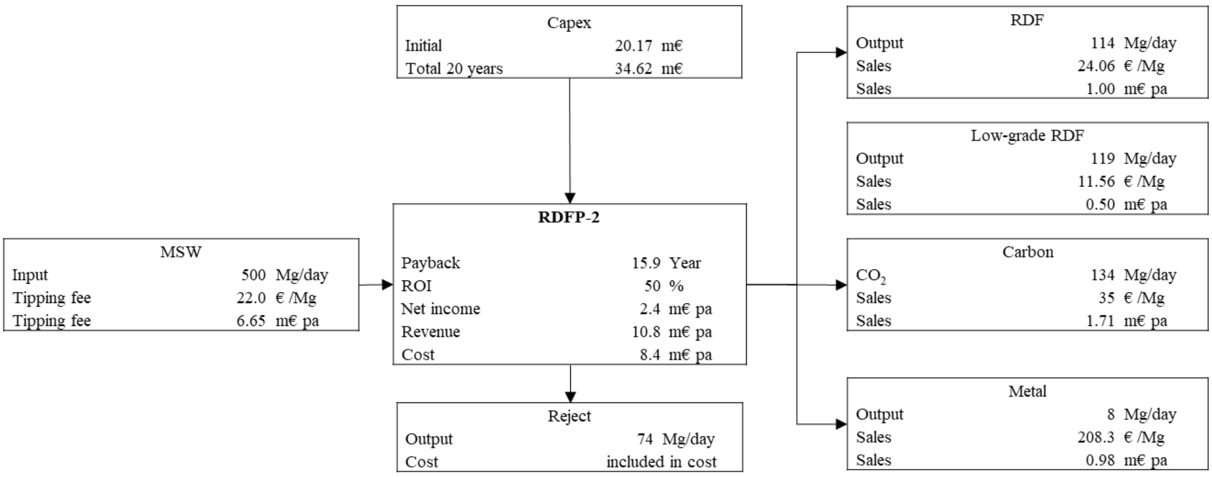

Figure 7. 6 Summary of RDFP-2 Financial Analysis Over 20 Years

7.3 RDFP-3: RDF & Low-grade RDF Drying in the Cement Plant

RDFP-3 incorporated Strategy 3 from the initial pilot project and was enhanced by integrating a drying process using box dryers located at the cement plant. The pre-drying process generally occurred close to the cement plant. The dryers utilized hot gas from the bag filter, operating within a temperature range of 130-175°C. Each box dryer had a capacity of 270 Mg.

For processing, two units were designated for materials with dimensions exceeding 80 mm, while a separate unit handled materials with dimensions below 80 mm. The drying operation used a batch system, which lasted one day and required two units for each material size. This approach ensured efficient thermal management and effective drying of the RDF.

To optimize thermal efficiency, the box dryers were designed with features that maximized heat transfer from the hot gas to the RDF. The design included careful placement of heating elements and airflow management to ensure uniform heating and drying. The integration of these dryers allowed for more precise control of the drying conditions, leading to improved quality and consistency of the RDF output. This systematic approach not only enhanced the overall efficiency of the drying process but also contributed to better utilisation of the available thermal energy. The procedural flow of the RDFP-3 model is illustrated in Figure 7.7

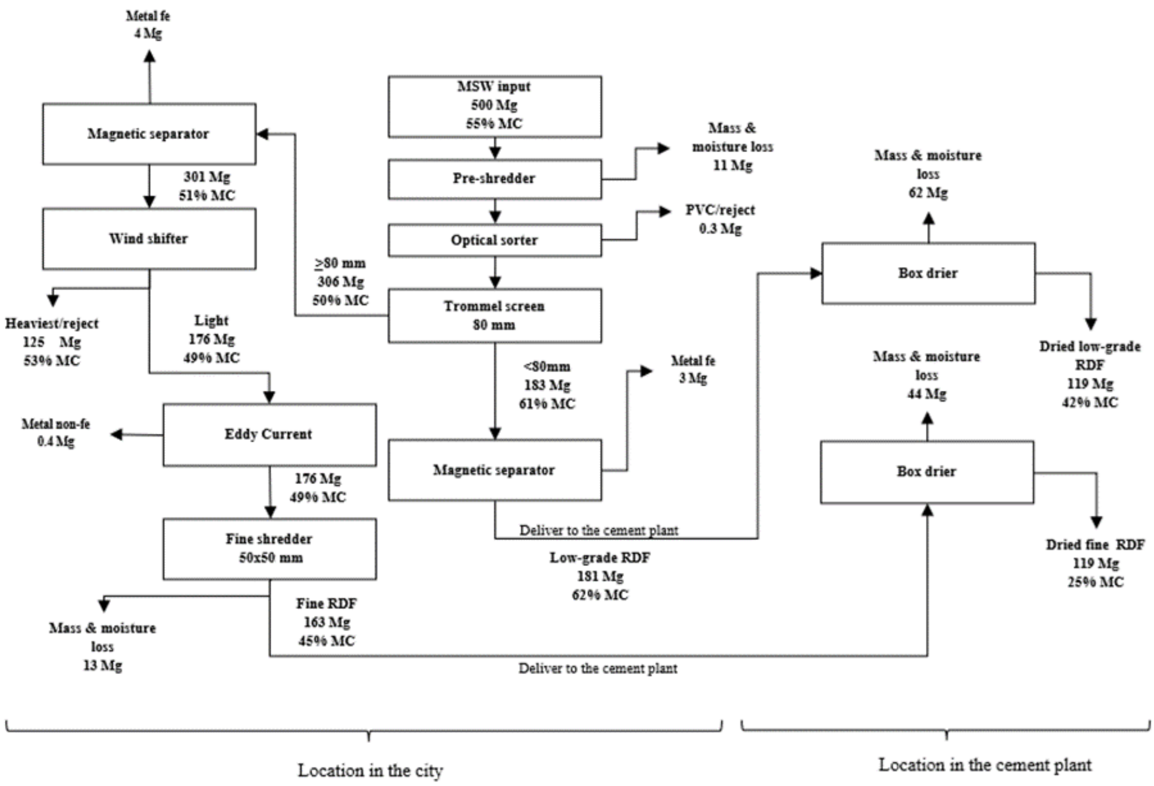

Figure 7. 7 Modelling Result of RDFP-3

The cement plant's intake of RDF and low-grade RDF followed a specific handling and processing pathway. Initially, the materials were fed into a feeder receiving bunker and then conveyed to a box drier. Upon completion of the drying process, the RDF products would be transported to the calciner for consumption as outlined in the scheme presented in Figure 7.8.

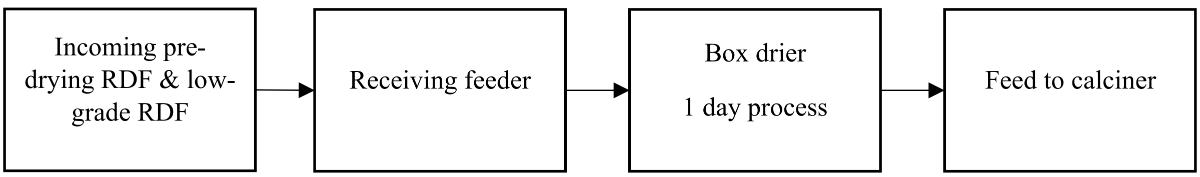

Figure 7. 8 RDFP-3 Handling Procedure in the Cement Plant

To facilitate a better understanding, Figure 7.9 on the subsequent page offers an elaborate representation of the box drying process designated for the RDFP-3 model. This depiction specifies the unique design and operational aspects of the drying system, crucial for the fuel's preparation before its application to the calciner.

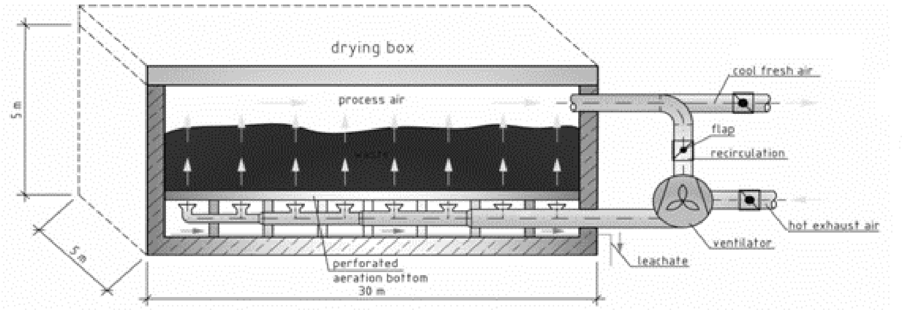

Figure 7. 9 RDFP-3 Sketch of Box-drier
Figure taken from Heidelberg Material, (2024)

The box dryer testing was conducted at one of the Heidelberg Material plants in China, where it demonstrated key performance metrics, as shown in Table 7.13 below.

Table 7. 13 Box-drier Keys Performance

Type	Concrete with grab crane
Components	Crane, flap, ventilator, leachate tank, aeration pipe, ducting
Gas temperature input	130-175^{0}C
Hot gas source	Hot gas exit from bag filter
Air blowing capacity	24 m^3/min
Total installed power	2x120 kW
Moisture reduction	Input 55-60% wt. (ar.), output 30-35% wt. (ar.)
Dimension	5x30x5 m, optimal heap up to 4m
Capacity	270 Mg/day
Total	2 unit for RDF, and 2 unit for low-grade RDF

The box drier featured a concrete type with a grab crane, where the component elements included a crane, flap, ventilator, leachate tank, aeration pipes, and ducting to optimise the drying process. The gas temperature for input ranged from 130° to 175° C, sourced directly from the hot gas exit of a bag filter. With an air-blowing capacity of 24 m^3 per minute and a total installed power of 2x120 kW, the unit dimensions were suitable for an optimal heap height of up to 4 mm within a 5x30 m footprint. Each box drier had a notable capacity of 270 Mg/day, and 4 units were planned for the modelling, 2 for RDF and 2 for low-grade RDF, to strengthen the drying capabilities of the MSW management system. The proximity of the box drier system to an abundant heat source made it easily replicable, facilitating a straightforward duplication process. This advantageous location ensured that the drying system could effectively utilize the readily available existing thermal energy at the cement plant, thereby streamlining operations and potentially reducing costs associated with additional heat generation (Conceição & Rolim, 2019).

Table 7.14 summarizes the chemical quality and CO_2 savings of the RDFP-3 model. Out of the 500 Mg/day of MSW input, 119 Mg/day was converted into RDF and another 119 Mg/day into low-grade RDF, with both fractions contributing to a total AF delivery of 238 Mg/day to the cement plant, accounting for 48% of the input mass. While MC of the input was relatively high at 55%, the subsequent heating values were substantial, with RDF notably having a higher LHV of 16.4 MJ/kg compared to 5.9 MJ/kg for low-grade RDF, resulting in an impressive net heat production of 1,959 GJ/day from RDF alone. This effective use of RDF resulted in significant CO_2 savings, with daily reductions of 103 Mg from RDF and 20 Mg from low-grade RDF. This is a notable improvement compared to traditional coal, showcasing RDF's role in emissions reduction in the cement industry.

Table 7. 14 Summary of the RDFP-3 Model

Parameter	Unit	MSW Input	Output					
			RDF	Low-grade RDF	Rejected material	Metal	Moisture and mass loss	Total AF for the cement plant
Mass	Mg/day	500	119	119	125	7	130	238
Mass	%	100	24	24	25	1	26	48
MC	% wt. (ar.)	55	25	42	-	-	-	33
LHV	MJ/kg	5.6	16.4	5.9	-	-	-	11.2
Net heat	GJ/day	2,775	1,959	704	-	-	-	2,664
Ash	% wt. (db.)	11	20	17	-	-	-	19
S	% wt. (db.)	0.24	0.45	0.34	-	-	-	0.39
Cl	% wt. (db.)	0.36	0.72	0.50	-	-	-	0.61
C	% wt. (db.)	47	54	40	-	-	-	47
C	% wt. (ar.)	21	40	23	-	-	-	32
Biomass content	%	60	50	52	-	-	-	51
CO_2 emission factor	Kg CO_2/GJ	55.2	45.0	68.5	-	-	-	56.8
CO_2 emission factor difference compared to coal (97.6)	Kg CO_2/GJ	42.4	52.6	29.1	-	-	-	40.9
CO_2 savings	Mg/day		103	20	-	-	-	123

Next, a detailed Capex for RDFP-3 is presented in Table 7.15, beginning with the pre-operation expenses totalling €84,000. Additional information regarding the costs of equipment and building-civil works is also shown in Table 7.15 on the following page.

Table 7. 15 Capex for Equipment RDFP-3

No	Equipment	Lifetime	Total Capacity	Total Unit	Total Cost Includes VAT
		Year	Mg/Day		€
1	Hopper, dosing and feeder	15	600	1 set	230,714
2	Truck scale	15	600	2	138,429
3	Pre-shredder	10	600	2	1,195,100
4	Optical sorter	10	600	1	357,143
5	Trommel	10	600	4	2,191,786
6	Magnetic separator	10	600	4	403,750
7	Wind-shifter	10	300	1	314,925
8	Eddy current	10	270	1	288,393
9	High speed fine shredder	10	270	1	1,038,214
10	Box-drying	10	950	4	1,000,000
11	Conveyor system	8	600	1 set	531,358
12	Loader	8	600	2	173,036
14	Dump truck	8	600	3	155,732
15	Crane	8	600	1	95,170
16	Power transmission	15	-	1 set	213,411
17	Electric and control system	15	-	1 set	99,117
18	Equipment substructure	15	-	1 set	273,973
19	Pipe and blower system	15	-	1 set	86,735
20	Laboratory	15	-	1 set	144,196
21	Instrument	15	-	1 set	144,196
22	Safety & monitoring	15	-	1 set	173,036
23	**Total**				9,248,413

The total Capex for procuring essential equipment came to €9,248,413, with a roster of components that included everything from hoppers and shredders to trommels and magnetic separators, tailored to meet various lifespan requirements and operational capacities. Significant financial investments were directed toward pre-shredders at €1,195,100 and trommels at €2,191,786, underscoring the importance and expenses of these core machinery pieces.

Costs linked to the drying system and conveyors also represented major Capex outlays, indicative of their pivotal roles in the plant's ability to process a substantial daily throughput of up to 540 Mg of MSW material, capable of receiving an amount of 500 Mg/day. This equipment is part of a broader infrastructural framework, with a detailed cost breakdown provided in Table 7.16. The table focuses on the expenditures related to building construction and civil works for the RDFP-3 project.

Table 7. 16 Capex of Building-Civil Works in RDFP-3

No	Building/Civil Works	Area	Lifetime	Total Cost Includes VAT
		m^2	years	€
1	Treatment area	2,500	20	1,190,476
2	RDF storage	2,000	20	833,333
3	Security	21	20	10,000
4	Gate	56	20	26,667
5	Office & Laboratory	500	20	238,095
6	Workshop	500	20	238,095
7	Safety & fire	300	20	142,857
8	Housing	100	20	47,619
9	Central control room	150	20	71,429
10	Utility	500	20	238,095
11	Electrical	700	20	333,333
12	Truck scale area	350	20	166,667
13	Washing area	240	20	114,286
14	Road, drainage, & landscape	2,375	20	282,750
17	Box-drying	600	20	607,143
18	Land preparation		20	98,343
	Total	**10,892**		4,639,188

The RDFP-3 required roughly 1.1 hectares of land. The total Capex for processing 500 Mg of MSW per day, or 182,500 Mg yearly, was expected to be around €14.4 million. Table 7.17 presents a 20-year Capex projection, detailing investments corresponding to equipment lifespans.

Table 7. 17 Estimated Total Capital Expenditure Over 20 Years for RDFP-3

Item	Unit	Initial Year	Year 9	Year 11	Year 16	Total
Pre-operation cost	€	83,333	-	-	-	83,333
Equipment	€	9,644,413	1,522,596	11,519,033	2,426,787	25,112,829
Building-civil works	€	4,639,188	-	-	-	4,639,188
Total	€	14,366,934	1,522,596	11,519,033	2,426,787	29,835,351

Table 7.18 on the following page presents a financial projection illustrating the expected revenue for the initial year and an average over a 20-year period from the RDFP-3 model's operations, assuming it is fully operational and generating income. The table analyses financial data, highlighting the impact of carbon sales on revenue. Carbon sales from RDF and low-grade RDF were significant, with year 1 revenues of €1,258,331 and €261,516, respectively. The total year 1 revenue was €7,532,614, with a 20-year average of €10,544,661. This emphasises the importance of carbon sales in revenue.

Table 7. 18 Revenue of RDFP-3

Item	Unit Price Year 1	Quantity	Total Revenue Year 1	Average Revenue 20 Years
	€/Mg	Mg/year	€	€
Tipping fee of MSW	22.0	182,500	4,019,345	6,645,174
RDF	24.4	41,683	1,019,126	1,019,126
Low-grade RDF	8.9	43,280	383,114	383,114
Metal	208.3	2,838	591,182	977,399
Carbon sales by RDF	35.0	37,590	1,258,331	1,258,331
Carbon sales by low-grade RDF	35.0	7,471	261,516	261,516
Total	23.9	315,361	7,532,614	10,544,661

Table 7.19, provides a detailed breakdown of RDFP-3's costs and net income. The RDFP-3 model's financial overview indicates a strategic balance between Capex and Opex, highlighting significant equipment maintenance and electricity costs. This balance is crucial for long-term sustainability, as it allows for the allocation of funds to areas that maximise operational efficiency. Labour and equipment depreciation were the primary fixed costs, which remained relatively stable over time. Over 20 years, total costs rose, but net income per Mg of MSW increased, suggesting efficiency gained. These gains were a testament to the model's effective cost management and technological advancements. The model predicted a 6-year payback period and a 92% ROI, affirming its financial viability and profitability and positioning it as a competitive option in the waste-to-energy market.

Table 7. 19 Cost and Net Income of RDFP-3

Cost	Unit	Year 1	20 Years Average
Variable cost			
RDF transportation to the cement plant	€	310,139	570,432
Low-grade RDF transportation to the cement plant	€	257,616	473,828
Reject transportation	€	455,587	837,952
Maintenance: building-civil works	€	92,784	170,655
Maintenance: equipment	€	964,441	1,773,877
Electricity	€	517,423	951,685
Fuel	€	380,121	699,150
Total variable cost	€	2,978,111	5,477,579
Fix cost			
Labour	€	639,167	951,658
Equipment depreciation	€	886,692	886,692
Building-civil works depreciation	€	201,602	201,602
Insurance	€	28,231	28,231
Total fix cost	€	1,755,692	2,068,183
Total Cost	€	4,733,803	7,545,762
Debt bearing	€	1,572,689	78,634
Income before tax (revenue-total cost)	€	1,226,122	2,605,727
Tax income	€	269,747	573,260
Net income	**€**	**956,375**	**2,032,467**
Net income	€/Mg of MSW	5	11
Opex	**€**	**3,617,278**	**6,429,236**
Opex	€/Mg of MSW	20	35
Payback period	**Year**	**6.0**	
ROI	**%**		**92**

Figure 7.10 below provides an overview of the financial model for RDFP-3. This snapshot captures essential financial components such as Capex, payback, ROI, revenue, and costs. Understanding these elements is vital for evaluating the project's financial health and overall feasibility.

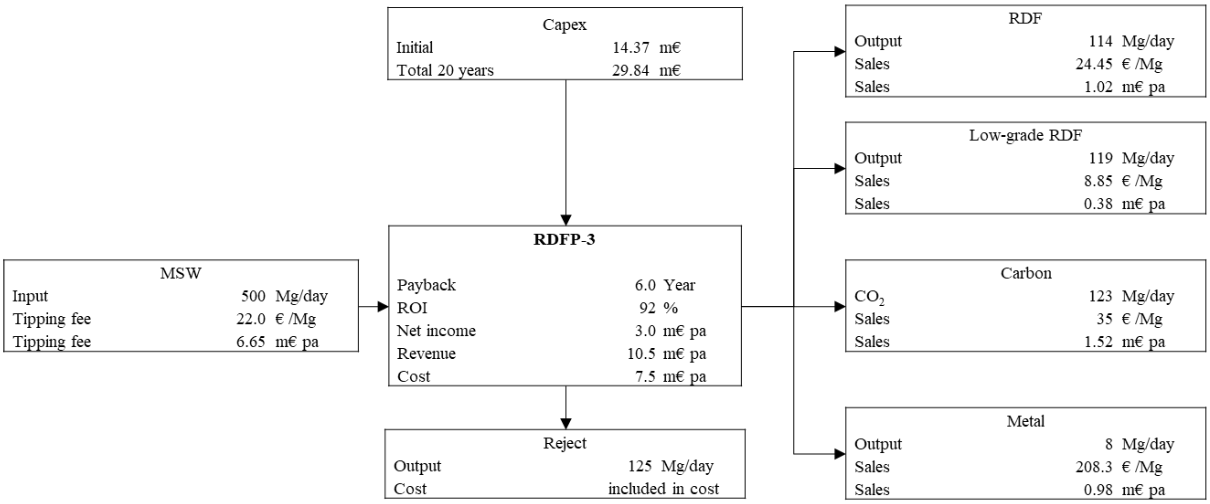

Figure 7. 10 Summary of RDFP-3 Financial Analysis Over 20 Years

7.4 RDFP- 4: Thermal Belt Drier with Bio-drying for the Low-grade RDF

RDFP-4 adopted strategy 4 from the pilot project and was similar to RDFP-2's processes for the materials smaller than 80 mm. It included bio-drying for materials smaller than 80 mm, utilising a turning machine with the assistance of sunlight through a transparent roof for 13 days. As for the drying of materials larger than 80 mm, it relied on a belt dryer. Figure 7.11, provided below, illustrates the flow process for the RDFP-4 model.

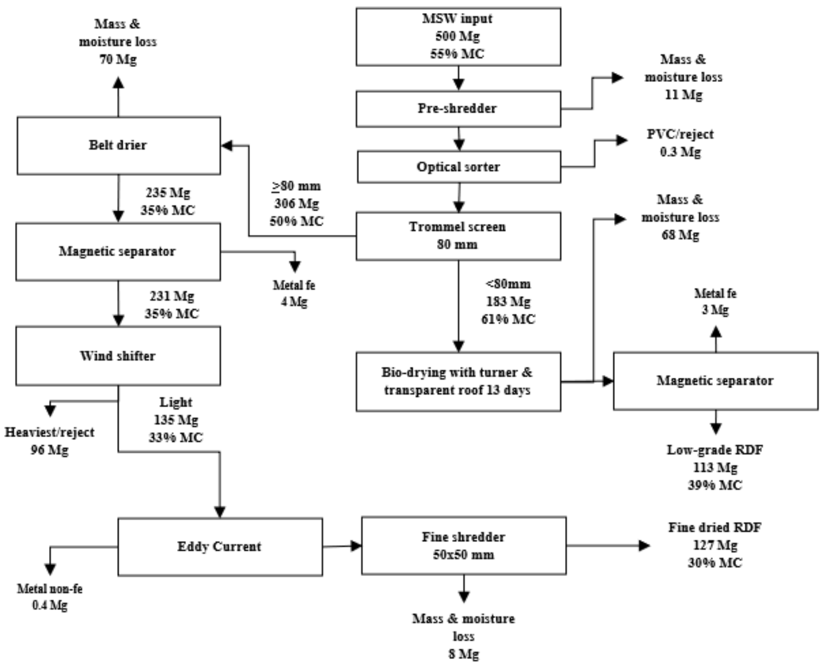

Figure 7. 11 Modelling Result of RDFP-4

Table 7.20 summarises the RDFP-4 model, including quality and CO_2 emissions data, as indicated in the previous figure. From the daily input of 500 Mg of MSW, substantial masses were converted to RDF (127 Mg) and low-grade RDF (113 Mg), contributing to the total AF supplied to the cement plant of 239 Mg. With definite MC of 30% for RDF and 39% for low-grade RDF, their respective LHVs were 15.2 and 6.4 MJ/kg, respectively. These translated into notable net heat contributions of 1,926 and 726 GJ/day, respectively, totalling about 2,652 GJ/day when combined with the net heat from rejected materials. Although the biomass content varied across different outputs, the effective CO_2 emission factors were significantly lower than those of coal. This is evident from a reduction of 101 Mg/day and 23 Mg/day in CO_2 emissions from RDF and low-grade RDF, respectively, culminating in a daily CO_2 saving of 124 Mg. This data highlights the environmental benefits and energy recovery efficiency of converting MSW to RDF within the scope of cement manufacturing.

Table 7. 20 Summary of the RDFP-4 Model

Parameter	Unit	MSW Input	Output					
			RDF	Low-grade RDF	Rejected material	Metal	Moisture and mass loss	Total AF for the cement plant
Mass	Mg/day	500	127	113	96	8	157	239
Mass	%	100	25	23	19	2	31	48
MC	% wt. (ar.)	55	30	39	-	-	-	34
LHV	MJ/kg	5.6	15.2	6.4	-	-	-	11.1
Net heat	GJ/day	2,775	1,926	726	-	-	-	2,652
Ash	% wt. (db.)	11	19	18	-	-	-	18
S	% wt. (db.)	0.24	0.42	0	-	-	-	0.39
Cl	% wt. (db.)	0.36	0.68	1	-	-	-	0.61
C	% wt. (db.)	47	54	38	-	-	-	46
C	% wt. (ar.)	21	38	24	-	-	-	31
Biomass content	%	60	50	52	-	-	-	51
CO_2 emission factor	Kg CO_2/GJ	55.2	45.1	66.5	-	-	-	55.2
CO_2 emission factor difference compared to coal (97.6)	Kg CO_2/GJ	42.4	52.5	31.1	-	-	-	42.4
CO_2 savings	Mg/day		101	23	-	-	-	124

Subsequently, a detailed account of the capital expenditures for RDFP-4 is provided, starting with the pre-operation costs that amount to €84,000. Additional financial information related to equipment and building-civil works costs is listed in Tables 7.21 and 7.22.

Table 7. 21 Capex for Equipment in RDFP-4

No	Equipment	Lifetime	Total Capacity	Total Unit	Total Cost Includes VAT
		Year	Mg/Day		€
1	Hopper, dosing and feeder	15	600	1 set	230,714
2	Truck scale	15	600	2	138,429
3	Pre-shredder	10	600	2	1,195,100
4	Optical sorter	10	600	1	357,143
5	Turning machine	8	300	1	648,884
6	Trommel	10	600	4	2,191,786
7	Magnetic separator	10	600	4	403,750
8	Wind-shifter	10	300	1	314,925
9	Eddy current	10	270	1	288,393
10	High-speed fine shredder	10	270	1	1,038,214
11	Belt drier	10	300	2	904,524
12	Conveyor system	8	600	1 set	531,358
13	Loader	8	600	2	173,036
14	Dump truck	8	600	3	155,732
15	Crane	8	600	1	95,170
16	Power transmission	15	-	1 set	213,411
17	Electric and control system	15	-	1 set	246,342
18	Equipment substructure	15	-	1 set	273,973
19	Pipe and blower system	15	-	1 set	86,735
20	Laboratory	15	-	1 set	144,196
21	Instrument	15	-	1 set	144,196
22	Safety and monitoring	15	-	1 set	173,036
	Total				9,949,046

The table above details the costs for key equipment totalling €9,949,046, with major expenses for trommels and shredders essential to processing 540 Mg/day. The Capex covered a range of machinery and related infrastructure necessary for a fully operational facility, from hoppers and scales to an advanced electric and control system.

Table 7. 22 Capex of Building-Civil Works in RDFP-4

No	Building/Civil Works	Area	Lifetime	Total Cost Includes VAT
		m^2	years	€
1	Treatment area	2,500	20	1,190,476
2	RDF storage	2,000	20	833,333
3	Security	21	20	10,000
4	Gate	56	20	26,667
5	Office & Laboratory	500	20	238,095
6	Workshop	500	20	238,095
7	Safety & fire	300	20	142,857

Table 7. 22 Capex of Building-Civil Works RDFP-4 (continue)

No	Building/Civil Works	Area	Lifetime	Total Cost Includes VAT
		m^2	years	€
9	Central control room	150	20	71,429
10	Utility	500	20	238,095
11	Electrical	700	20	333,333
12	Truck scale area	350	20	166,667
13	Washing area	240	20	114,286
14	Road, drainage, & landscape	2,375	20	282,750
17	Bio-drying area (30 lanes, 4.5mx28m) with transparent roof	6,804	20	2,835,000
18	Land preparation		20	169,218
	Total	**17,096**		6,937,920

The facility's infrastructure required significant investment, with the treatment area and RDF storage costing €1,190,476 and €833,333, respectively, each lasting 20 years. Other facilities, including security, offices, labs, and a bio-drying area, amounted to €6,937,920 for 1.7 hectares. Table 7.23 provides a 20-year Capex forecast, detailing investments corresponding to equipment renewal periods.

Table 7. 23 Estimated Total Capital Expenditure Over 20 Years for RDFP-4

Item	Unit	Initial Year	Year 9	Year 11	Year 16	Total
Pre-operation cost	€	83,333	-	-	-	83,333
Equipment	€	10,345,046	2,556,819	11,348,050	4,075,181	28,325,095
Building-civil works	€	6,937,920	-	-	-	6,937,920
Total	€	17,366,300	2,556,819	11,348,050	4,075,181	35,346,349

A financial projection of the RDFP-4 model outlines the anticipated revenue for the first year and the average over a 20-year period, as indicated in Table 7.24 on the following page. This was based on the assumption that the model is fully operational and generating income. The main income came from the MSW tipping fee, yielding €4,019,345 initially and an average of €6,645,174 over 20 years. Refined RDF, low-grade RDF, and recycled metals sales added revenues of €1,019,126, €414,671, and €591,182, respectively. Carbon credit sales from RDF and low-grade RDF contributed €1,256,686 and €511,331, respectively. The total first-year revenue was €7,812,341, with a 20-year average of €10,824,388.

Table 7. 24 Revenue of RDFP-4

Item	Unit Price Year 1	Quantity	Total Revenue Year 1	Average Revenue 20 Years
	€/Mg	Mg/year	€	€
Tipping fee of MSW	22.0	182,500	4,019,345	6,645,174
RDF	24.4	41,683	1,019,126	1,019,126
Low-grade RDF	9.6	43,280	414,671	414,671
Metal	208.3	2,838	591,182	977,399
Carbon sales by RDF	35.0	39,775	1,256,686	1,256,686
Carbon sales by low-grade RDF	35.0	8,234	511,331	511,331
Total	24.5	318,309	7,812,341	10,824,388

Table 7.25 provides an overview of the costs and net income associated with the RDFP-4. In year 1, variable costs, including transportation and maintenance, were €3,429,120, while fixed costs like labour and depreciation were €1,988,257. The overall cost reached €5,417,378, with a net income of €386,755 after taxes. Over 20 years, the average total cost was €8,607,859, with a net income of €1,358,563. The Opex per Mg of MSW started at €22 and increased to €40. The facility expected a payback period of 19.7 years and a ROI of 51%. The subsequent Figure 7.12 illustrates a summary of the financial analysis for this model.

Table 7. 25 Cost and Net Income of RDFP-4

Cost	Unit	Year 1	20 Years Average
Variable cost			
RDF transportation to the cement plant	€	310,139	570,432
Low-grade RDF transportation to the cement plant	€	257,616	473,828
Reject transportation	€	351,285	646,111
Maintenance: building-civil works	€	138,758	255,215
Maintenance: equipment	€	1,034,505	1,902,743
Electricity	€	839,375	1,543,845
Fuel	€	497,443	914,936
Total variable cost	€	3,429,120	6,307,111
Fix cost			
Labour	€	639,167	951,658
Equipment depreciation	€	968,070	968,070
Building-civil works depreciation	€	346,896	346,896
Insurance	€	34,125	34,125
Total fix cost	€	1,988,257	2,300,748
Total Cost	€	5,417,378	8,607,859
Debt bearing	€	1,899,124	94,956
Income before tax (revenue-total cost)	€	495,839	1,741,748
Tax income	€	109,085	383,184
Net income	**€**	**386,755**	**1,358,563**
Net income	€/Mg of MSW	2	7
Opex	**€**	**4,068,287**	**7,258,768**
Opex	€/Mg of MSW	22	40
Payback period	**Year**	**19.7**	
ROI	**%**		**51**

Figure 7.12 below offers an overview of the financial model for RDFP-4. This summary highlights key financial components including Capex, pay back, ROI, revenue, and costs. Grasping these elements is crucial for assessing the project's financial viability and overall feasibility.

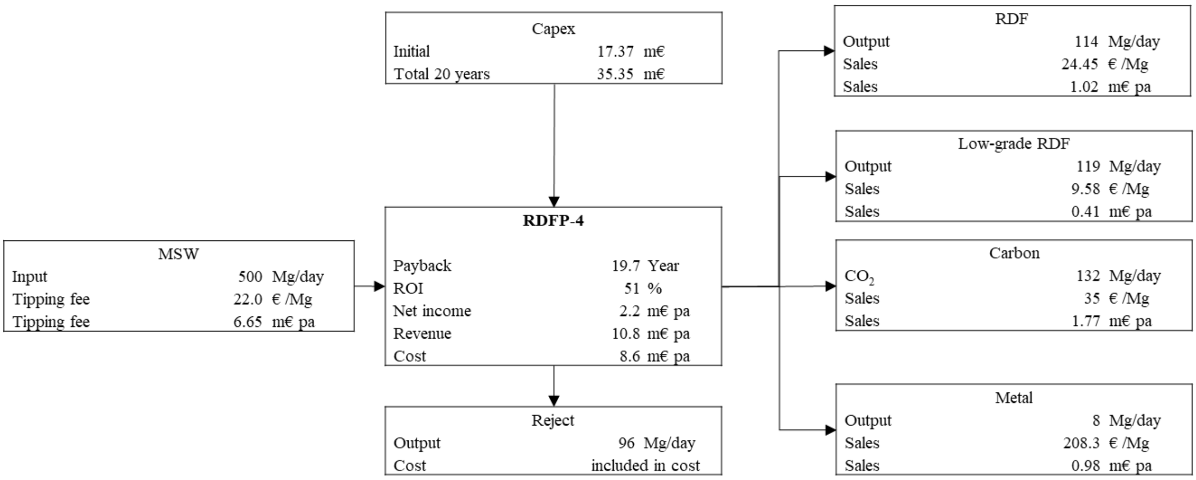

Figure 7. 12 Summary of RDFP-4 Financial Analysis Over 20 Years

7.5 Comparisons of the Models and Recommendations

Section 7.5 primarily focuses on the quantity and quality of the modelled outputs for RDF and low-grade RDF, as illustrated in Figure 7.13.

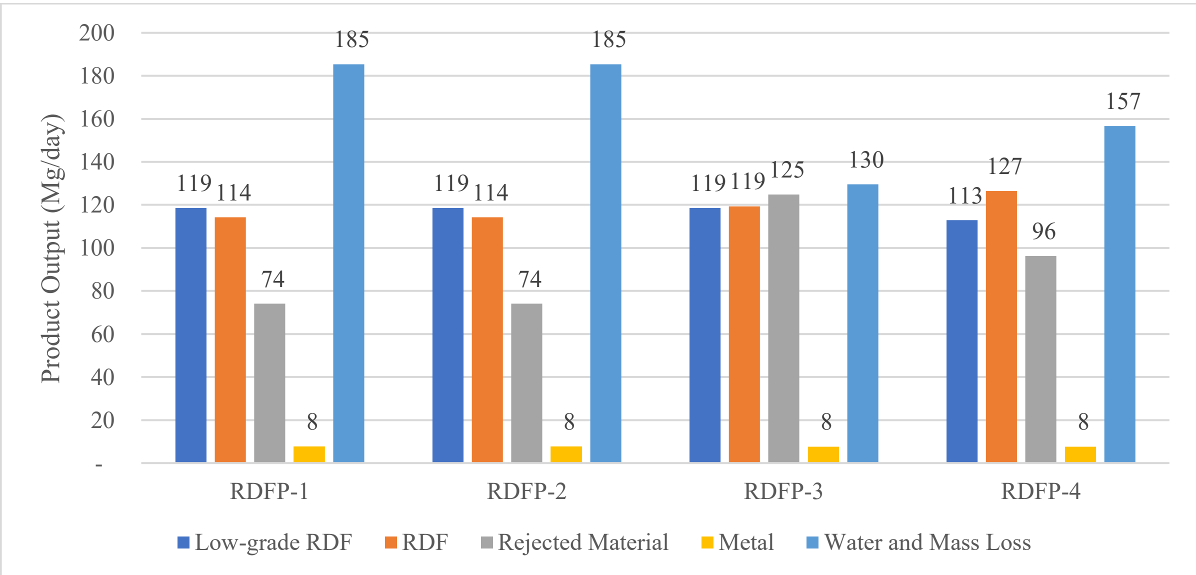

Figure 7. 13 Product Output of Modelling

In the modelling, there was a significant discrepancy in the quantity of low-grade RDF, particularly in RDFP-3, due to the capacity of the thermal drying system. This quick, 1-day drying process could not achieve the same dryness level as the 13-16 days bio-drying method applied in RDFP-1 and RDFP-2 or the <80 mm fraction in RDFP-4. The rapid drying approach was intended to reduce land use, which was needed for a longer drying approach.

Table 7. 26 RDF Quality Result

Parameter	Unit	RDFP-1	RDFP-2	RDFP-3	RDFP-4
MC	%wt. (ar.)	27	27	25	30
HHV	MJ/kg	19.0	19.0	19.2	18.2
LHV	MJ/kg	16.1	16.1	16.4	15.2
Ash	%wt. (db.)	16	16	20	19
S	%wt. (db.)	0.43	0.43	0.45	0.42
Cl	%wt. (db.)	0.69	0.69	0.72	0.68

Table 7.26 showcases the quality assessment for RDF resulting from RDFP-1 to RDFP-4. The MC of the output spanned a range of 25% to 30% across the different processing plants. HHV values demonstrated relatively minor variation, recorded between 18.2 MJ/kg and 19.2 MJ/kg, while LHV values extended from 15.2 MJ/kg to 16.4 MJ/kg. RDF from RDFP-3 had the highest ash content (20%), followed by the RDF from RDFP-4 at 19%. It should be noted that in RDFP-3 and RDFP-4, the ash content is higher, which is influenced by the reduced efficiency of the trommel as it separates MSW in a wet state, with an MC of 55%. S content fluctuated marginally around 0.42-0.45%, and Cl content uniformly exceeded 0.68% across all facilities. When compared against the RDF standard EN 21640:2021, all these RDFs fell into classification class 3 and complied with the Indonesian standards. Meanwhile, according to the cement plant specifications, all these RDFs were categorized under Spec 4.

Compared to other studies that utilised superior separation technologies like briquetting and source from previously sorted MSW, the ash content tends to be below 10% (Alfè et al., 2022; Ramadhan & Oktavia, 2022).

Table 7. 27 Low-grade RDF Quality Result

Parameter	Unit	RDFP-1	RDFP-2	RDFP-3	RDFP-4
MC	%wt. (ar.)	31	31	42	39
HHV	MJ/kg	9.8	9.8	8.3	8.7
LHV	MJ/kg	7.8	7.8	5.9	6.4
Ash	%wt. (db.)	30	30	17	18
S	%wt. (db.)	0.40	0.40	0.34	0.36
Cl	%wt. (db.)	0.59	0.59	0.50	0.53

Table 7.26 presents the quality assessment results for low-grade RDFs. According to EN 21640:2021, all the low-grade RDFs were under Spec 5, while based on Indonesian specifications, none met the standard criteria. Nonetheless, according to the cement plant specs,

the products fell under Spec 5. The cement plant provides leniency in meeting specifications, which can promote more efficient and straightforward MSW management.

Overall, these output products had a high MC, which in part could be due to the high organic content composition. The organic content could be further dried by extending the drying process, for instance, bio-drying could be extended beyond 21 days to reduce moisture below 20% (Noori et al., 2022). The differences in MC, highest in RDFP-3 at 42% and lowest in RDFP-1 and RDFP-2 at 31%, were due to variations in the drying process. Moreover, the high ash content of the low-grade RDF from RDFP-1 and RDFP-2 was due to the abundance of non-combustible materials. This was not a significant issue for cement plants when the products were fed into the calciner, as the ash contains raw cement materials such as silica (Chatterjee, 2018).

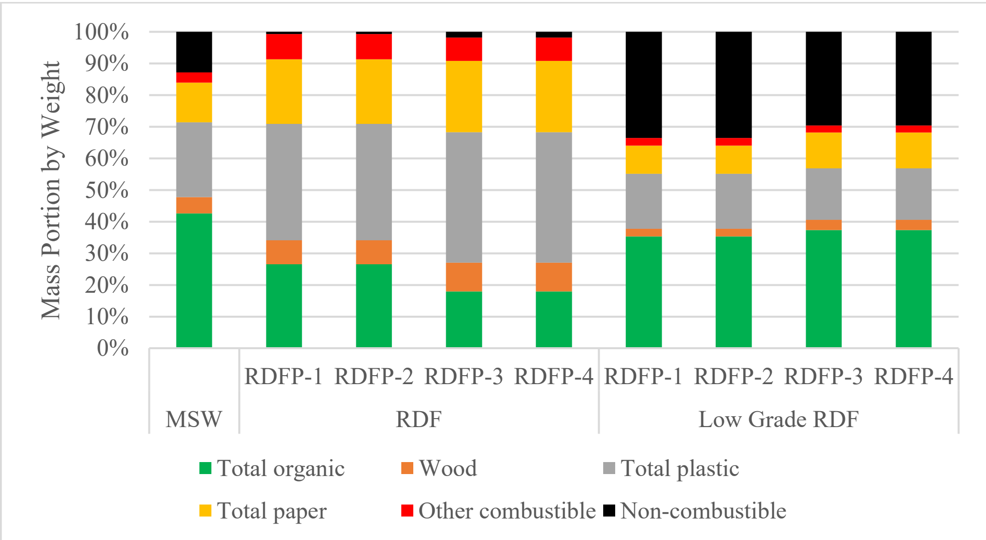

Figure 7. 14 Material Fraction of each Modelling

Table 7.14 presents a comparison of the material fraction resulting from the modelling. In MSW, total organic material constituted the largest fraction at 43%, while in RDF, this percentage decreased significantly, with the lowest in RDFP-3 and RDFP-4 at 18%. Wood content in RDF was enhanced by its MSW composition but was reduced in low-grade RDF. Total plastic had a considerable increase in RDF fractions, accounting for over a third of the composition, notably higher than in MSW. RDF paper content also increased compared to MSW, indicating a higher potential for energy recovery through combustion. Other combustibles showed a rise in RDF but remained low in low-grade RDF. The non-combustible fraction had a marked decrease in RDF, emphasising the efficiency of the separation process.

Conversely, a substantial portion of the non-combustible remained in low-grade RDF, indicative of lower separation efficiency or a different processing system. The decline in organic content and the corresponding increase in plastic and paper content in RDF, compared to MSW, serve as factors that enhance the quality of RDF due to the higher carbon content. This enriched carbon proportion contributes to a greater energy value, making RDF a more efficient fuel than its unprocessed state (Kuspangaliyeva et al., 2021). In the case of low-grade RDF, the content of non-combustible material was significantly higher compared to RDF. This is due to many non-combustible fractions passing through the <80 mm sieve, leading to a high ash content in the low-grade RDF resulting from the abundant non-combustible constituents (Kuyumcu, 2018).

Next, an analysis was carried out to highlight the factors that distinguish one financial scenario from another. This part of the analysis spots the variations in upfront costs essential to setting up each model, indicating how these differences may impact the overall financial outlook. The comparison of initial Capex across each model is shown in Figure 7.15 below.

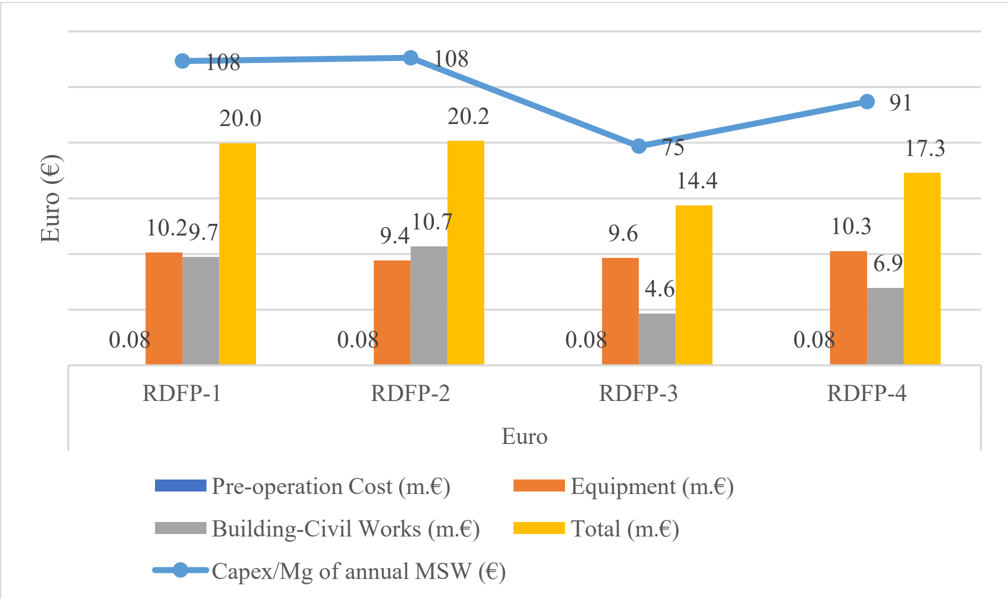

Figure 7. 15 Initial Capex Comparison of the Modellings

RDFP-1 and RDFP-2 incurred the highest Capex, primarily influenced by the land required for the bio-drying process. RDFP-1 required a land area of 2.9 hectares, RDFP-2 required 2.6 hectares, RDFP-3 needed only 1.1 hectares, and RDFP-4 needed 1.7 hectares. As for equipment, the costs were relatively similar across the models. Notably, RDFP-1 featured membrane bio-drying technology, RDFP-2 incorporated a turning machine, and RDFP-3 and

RDFP-4 utilised more trommels to address the low-performance issues when processing high moisture MSW. Among all the models, RDFP-3 was the most cost-effective, with a Capex of €14.4 million, equating to approximately €75 per Mg of annual MSW. The Capex cost per annual MSW for all these RDF models ranged from €75 to €91 per Mg, below the maximum limit set by the Coordinating Ministry for Maritime Affairs and Investment of Indonesia. According to the Ministry, for an MSW treatment facility to be feasible, the Capex should not exceed €100 per Mg of annual MSW (Menkomarves, 2023). On a broader scale, the Capex range in Asia for RDF is from €50 to €150 per Mg of annual MSW, averaging between €80 to €100 per Mg (Aleluia & Ferrão, 2017). Meanwhile, Europe's average annual MSW is approximately €120 to €400 per Mg (Shmurak & Matveev, 2022).

Table 7. 28 Annual Electricity Cost of the Modellings

Item	Unit	RDFP-1	RDFP-2	RDFP-3	RDFP-4
Installed electricity power	kWh	1250[1]	1250[1]	1250[1]	1910[1]
Effective electricity power	kWh	1063[1]	1063[1]	1063[1]	1623[1]
Cost/kWh	€	0.09	0.09	0.09	0.09
Annual cost	€	610,846	610,846	610,846	932,798
Specific electricity consumption	kWh/Mg of MSW	38	38	38	58

([1]Indocement, 2024)

Next, electricity consumption costs as part of Opex were calculated as shown in Table 7.28. The installed electricity data was obtained from the technology providers recorded in the Indocement database (Indocement, 2024). the electricity cost was based on the price set by the Indonesian government at 1,470 IDR/kWh (ESDM, 2022; Połomka & Jędrczak, 2019). A typical MBT plant has a specific electricity consumption ranging from 22.8 to 77.5 kWh/Mg of MSW. Meanwhile, the modelling had electricity consumptions ranging from 38 to 58 kWh per Mg of MSW.

Table 7. 29 Annual Fuel Cost of the Modellings

Item	Fuel (L/h)	Diesel Cost (€/L)	RDFP-1		RDFP-2		RDFP-3		RDFP-4	
			Total Unit	Total Cost (€)	Total Unit	Total Cost (€)	Total Unit	Total Cost (€)	Total Unit	Total Cost (€)
Turner	25	1.1	-	-	3	351,964	-	-	1	117,321
Loader	18	1.1	6	506,829	2	168,943	2	168,943	2	168,943
Dump Truck	10	1.1	3	140,786	3	140,786	3	140,786	3	140,786
Crane	15	1.1	1	70,393	1	70,393	1	70,393	1	70,393
Total				718,007	8	732,086	6	380,121	6	497,443

Subsequently, the fuel cost is presented in Table 7.29. The data on fuel consumption requirements was obtained from the Indonesian Survey Agency (LSI, 2021). To ensure comprehensive financial analysis, the labour cost data of MSW treatment, which includes the number of personnel and salary rates, is shown in Table 7.30. This data was also obtained from the same reference.

Table 7. 30 Annual Labour Cost of MSW Treatment

No	Position	No. of Person	Monthly Salary/person	Total Monthly Salary	Annual Salary
			€	€	€
1	Plant Manager	1	2,976	2,976	38,690
2	Production Head	1	2,381	2,381	30,952
3	Maintenance Head	1	2,381	2,381	30,952
4	Finance	2	714	1,429	18,571
5	Administration	2	714	1,429	18,571
6	SHE Section and Medical	2	714	1,429	18,571
7	Shift Supervisor	4	714	2,857	37,143
8	Shift Technician	4	714	2,857	37,143
9	Operator Central Control	4	714	2,857	37,143
10	Field & Heavy Equipment Operator	40	714	28,571	371,429
	Total	61		49,167	639,167

Table 7.31 provides details on transportation costs of RDF production plant material output to the Indocement cement plant. The data was derived from the actual procurement process at Indocement and sourced from suppliers in the West Java region.

Table 7. 31 Transportation Cost of Material Output to Indocement Cement Plant

Material	€/Mg
RDF	7.4
RDF low-grade	6.0
Rejected	10.0

(Indocement, 2024)

Subsequently, an analysis of debt servicing costs from all models over a five-year term is presented in Table 7.32. This analysis considers an annual interest rate of 2.89% for each model, as indicated. To provide a detailed overview, the impact of varying interest rates on the overall debt servicing costs is also examined in this section.

Table 7. 32 Debt Bearing Cost of the Modellings

Item	Unit	RDFP-1	RDFP-2	RDFP-3	RDFP-4
Interest Payment	€	(885,372)	(894,784)	(638,313)	(767,383)
Principal	€	(10,021,629)	(10,128,165)	(7,225,134)	(8,686,089)
Total	€	(10,907,001)	(11,022,949)	(7,863,446)	(9,453,471)

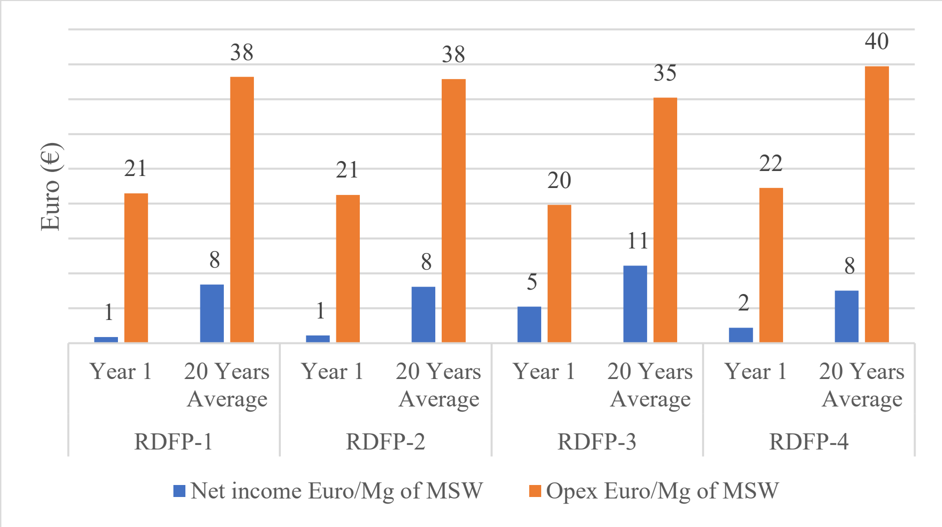

Figure 7. 16 Specific Net Income & Opex of Modellings

Figure 7.16 provides an illustration of specific net income and operating expenses per Mg of MSW from each model in the first and the twentieth years. Based on the financial parameters comparison over two-time frames, RDFP-3 outperformed other RDF production models with the highest net income per Mg of MSW, at €5 initially, rising to €11 over 20 years average, and recorded the lowest Opex, from €21 to €40. Other studies indicated net income per Mg of MSW at €6-7 and Opex from €7-30 in the first year (Tyagi et al., 2021; World Bank, 2017). RDFP-3 was found to be the most cost-efficient model, delivering higher income and incurring lower costs due to its minimal land and machinery requirements.

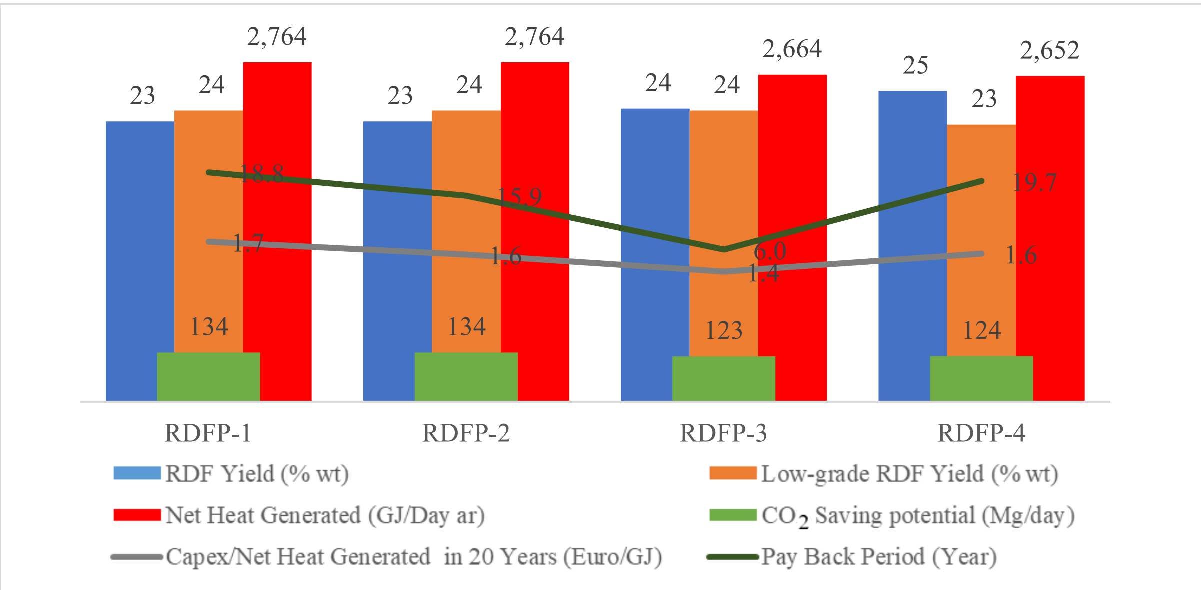

Figure 7. 17 Financial Performance Summary of the Modellings

Figure 7.17 showcases the optimal RDF production model that aligns with MSW reduction efforts and satisfies the cement plant's demand for alternative fuel. Across all models, the proportion of RDF and low-grade RDF produced was 23-25%, with a similar estimate for the net heat generated, ranging from 2,600 to 2,800 GJ/day. The estimated CO_2 savings from utilising these RDF products were also comparable, about 123-134 Mg/day. The shortest payback period was 6.0 years for RDFP-3. Other performance indicators to assess affordability or economic viability included the Capex/net heat generated over a 20-year service period. RDFP-3 emerged as the most cost-effective in this regard, with only €1.4/GJ. Therefore, RDFP-3 is recommended to be implemented as part of MSW management.

7.6 Aligning RDF Potential Quantity with the Cement Plant Target

This section analyses the potential RDF generated to achieve a 50% substitution rate of AF by 2030 from the total annual heat requirement estimated at 24,800 TJ or approximately 12,650 TJ. The assumptions incorporated into the analysis were the utilisation of the RDFP-3 model and the processing of 500 mg/day of MSW, which is considered one unit of the RDF production plant. Additionally, the reduction of CO_2 emissions compared to coal, which has an emission factor of 97.6 kg CO_2/GJ (Juhrich, 2022) and an LHV of 20.8 MJ/kg (Indocement, 2024), was calculated as a comparison. Table 7.33 below showcases the comparison of energy and CO_2 emissions for each AF proportion scenarios.

Table 7. 33 Energy and CO_2 Emission Impact of Coal and RDF Scenarios

Fuel Type	**Consumption**	**LHV**	**Net Energy Generation**	**AF Substitution**	**CO_2 Emission Factor**	**CO_2 Emission**
	Mg/year	(MJ/kg)	TJ/year	% heat	Kg CO_2/GJ	Mg /Year
Scenario 1: 100% Coal Consumption						
Low-grade RDF	-	5.9	-	-	34.6	-
RDF	-	16.4	-	-	16.2	-
Coal	1,194,311	20.8	24,800		97.6	2,420,480
Total	1,194,311	20.8	24,800	-	97.6	2,420,480
Scenario 2: 1 Unit of RDFP-Plant						
Low-grade RDF	43,276	5.9	257	1.0	68.5	17,625
RDF	43,581	16.4	715	2.9	45.0	32,215
Coal	1,147,485	20.8	23,828		97.6	2,325,579
Total	1,234,342	20.1	24,800	3.9	95.8	2,375,419
Potential coal reduction	46,826	-	-	-	-	-
Potential CO_2 Reduction	-	-	-	-	-	45,061

Table 7. 33 Energy and CO_2 Emission Impact of Coal and RDF Scenarios (continue)

Fuel Type	Consumption	LHV	Net Energy Generation	AF Substitution	CO_2 Emission Factor	CO_2 Emission
	Mg/year	(MJ/kg)	TJ/year	% heat	Kg CO2/GJ	Mg /Year
Scenario 3: 13 Units of RDFP-Plant						
Low-grade RDF	562,587	5.9	3,343	13.5	68.5	229,121
RDF	566,558	16.4	9,298	37.5	45.0	418,793
Coal	585,574	20.8	12,160		97.6	1,186,769
Total	1,714,719	14.5	24,800	51.0	74.0	1,834,683
Potential coal reduction	608,737	-	-	-	-	-
Potential CO_2 Reduction	-	-	-	-	-	585,797

To meet an energy requirement of 24,800 TJ in scenario 1 without AF, approximately 1.2 million Mg/year of coal was needed. However, with the adoption of RDF from just one recommended RDF Plant, as outlined in scenario 2, the substitution rate of AF was merely 3.9%, reducing coal consumption by 46,800 Mg/year and CO_2 emissions by around 45,000 Mg/year, or approximately 1.9%. Therefore, to achieve the target of a minimum 50% substitution rate of AF, 13 units of RDF plant would be required, as indicated in scenario 3. Implementing this would yield an AF substitution rate of 51%, decrease coal consumption by 608,000 Mg/year, and lower CO_2 emissions by 586,000 Mg/year, or 24.2%.

Constructing these 13 RDF plants based on the RDFP-3 model would necessitate a capital expenditure of 13 multiplied by €14.4 million, amounting to €186.8 million in total. The land required for this expansion would be 13 times 1.1 hectares, equating to approximately 14.3 hectares. The cement plant's utilisation of RDF could significantly diminish the daily volume of MSW from the four areas, with a reduction of 500 Mg/day of MSW per unit across 13 units, equalling a cut of 6,500 Mg/day of MSW. This reduction could account for 45% of the total daily MSW volume, especially considering the Jabodebek region generates up to 14,500 Mg/day of MSW.

7.7 The Potential Savings from the RDF Production Plant

This sub-chapter examines the potential savings from the operation of an RDF production plant for the city governments and the cement plant. The facility processes MSW across 13 units, with a total throughput of 6,500 Mg/day, as detailed in Sub-chapter 7.6. Table 7.34 presents the potential savings, highlighting that the city governments accrue savings from reduced landfilling costs while the cement plant benefits from a decrease in coal purchase expenses.

Table 7. 34 The Potential Savings from the RDF Production Plant

Cost	€/year	€/Mg
Cities Government		
Landfill operational	61,673	9.5[1]
Landfill maintenance	23,320	3.6[1]
Landfill fuel consumption	8,904	1.4[3]
Landfill leachate handling	5,890	0.9[3]
Landfill levy fees	52,244	8.0[1]
Total landfill cost	152,031	23.4
Tipping fee for the RDF production	143,155	22.0
Saving (total landfill cost - tipping fee for RDF production)	8,877	1.4
The Cement Plant		
Coal purchase	47,272,797	77.7[2]
Low-grade RDF purchase	4,980,066	8.9
Fine RDF purchase	13,852,147	24.4
Total RDF purchase	18,832,213	16.7
RDF operation and investment cost	28,228,618	25.0
Total RDF cost	47,060,832	41.7
Saving (coal purchase - total RDF cost)	211,966	0.2

([1]DLH Jakarta, 2023; [2]Indocement, 2024; [3]LSI, 2021)

Landfill costs were derived from actual data on MSW received at the Bantargebang landfill in 2023, amounting to 7,700 Mg/day, and were then calculated for 6,500 Mg/day of MSW. For the cement plant, the reduction in coal quantity was based on calculations in Table 7.33. Meanwhile, the RDF purchase costs were based on recommendations from modelling. The RDF operation and investment costs represented the expenses for handling RDF, including unloading, feeding, and the accrual of capital expenditures for the installation of feeding points, bag filters, and kiln modifications, including the installation of a chlorine bypass in the kiln over a 20-year period of RDF utilisation as modelled. According to the calculations, the potential savings to be received by the city governments were estimated at €8,877 per year, equivalent to €1.4/Mg of MSW. The savings for the cement plant were projected to be approximately €211,966 /year, or €0.2/Mg of fuel. This data indicates that there are savings for each party involved.

8. Environmental Review

8.1 The Environmental Impact of The Cement Process

The cement manufacturing process starts with raw material extraction, followed by crushing, blending, and calcination in a kiln to produce clinker. The clinker is then ground with additives to create cement. The manufacturing process has considerable environmental impacts. Globally, it accounts for about 27% of the total annual direct CO_2 emissions (IEA, 2018). The primary source of CO_2 emissions in the cement industry occurs during the production of clinker, an intermediate product for cement, where CO_2 is released from both the combustion of fuels for heating and the chemical decomposition of limestone (Liao et al., 2022). Furthermore, there are additional pollutants present, where the cement industry accounts for roughly 7.8% of nitrogen oxide emissions, 4.8% of sulfur oxide emissions, 5.2% of particulate matter (dust) emissions under 10 microns, and 6.4% of particulate emissions under 2.5 microns. These particulates originate from the raw materials, fuel, and the cement product itself (Miller & Moore, 2020). Pollutant materials from the cement process are emitted into various environmental media, leading to human health issues. These adverse effects can be transmitted to humans through direct means, such as the inhalation of air, and indirect pathways, via the distribution of media in soil, water, and other channels (Irshad et al., 2023). Given these impacts, it becomes crucial to pinpoint the origins of pollution within the cement industry. Figure 8.1 shows the range of pollutants emanating from a typical cement production plant, encompassing more than just air emissions.

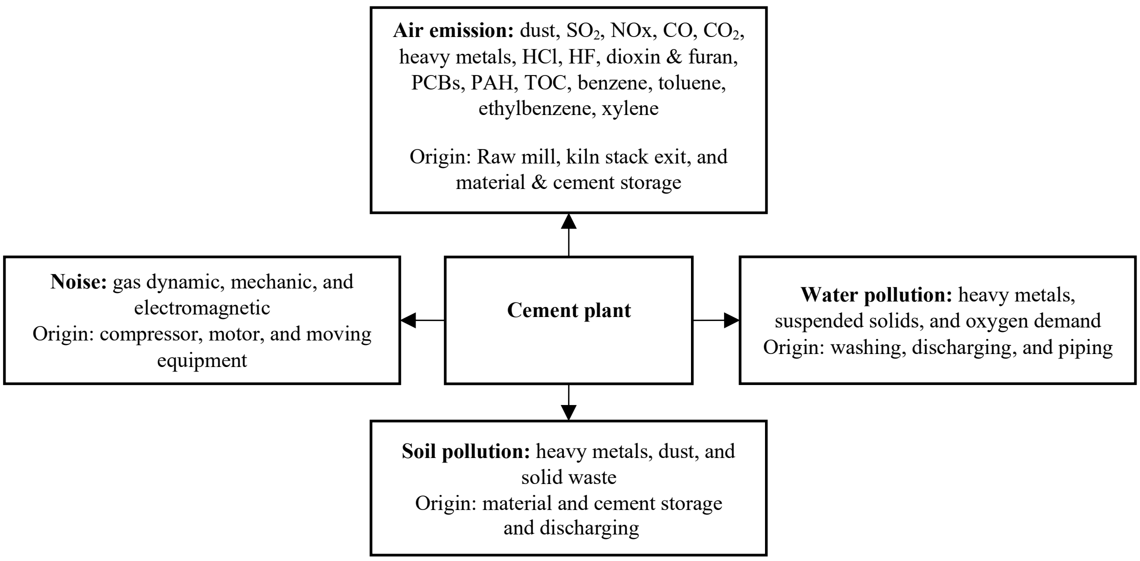

Figure 8. 1 Types of Pollutants from a Cement Plant
(VDZ, 2021; X. Zhu et al., 2022)

Because cement manufacturing is highly energy-intensive, the major environmental impacts that need to be considered are CO_2 and air pollutant emissions (Liu et al., 2021). Therefore, the subsequent section is dedicated to examining air pollutant emissions. In an effort to lessen these emissions, the cement industry is governed by a variety of emission standards at the international and national levels. These standards intend to decrease the volume of pollutants released into the atmosphere. Table 8.1 below presents an example of the emission standards applied to the cement industry.

Tabel 8. 1 Emission Standards of Cement Plant

No	Parameter	Unit	Indonesia	Germany
1	Total Particulate Matter/Dust	mg/Nm^3	60[1,2]	10[3,4]
2	SO_2	mg/Nm^3	650[1,2]	50[3,4]
3	NOx	mg/Nm^3	800[1,2]	200[3,4]
4	HCl	mg/Nm^3	20[1,2]	10[3,4]
5	Hg	mg/Nm^3	0.2[1,2]	0.03[3,4]
6	CO	mg/Nm^3	625[1,2]	50[3,4]
7	HF	mg/Nm^3	2[1,2]	1[3,4]
8	Cd	mg/Nm^3	0.2[1,2]	-
9	Pb	mg/Nm^3	5[1,2]	-
10	As	mg/Nm^3	1[1,2]	-
11	Ni	mg/Nm^3	0.5[1,2]	-
12	TOC	mg/Nm^3	100[1,2]	10[3,4]
13	Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V+Sn	mg/Nm^3	-	0.5[4]
14	Cd+Tl	mg/Nm^3	-	0.05[4]
15	Carcinogenic Substances (As, BaP, Cd, Co, and Cr)	mg/Nm^3	-	0.05[4]
16	NH_3	mg/Nm^3	-	30[3,4]
17	PCDD/F (Dioxin and Furan)	ng TEQ/Nm^3	0.1[1,2]	0.1[3,4]

([1]Indocement, 2023a; [2]KLHK, 2017; [3]Lahl et al., 2020; [4]VDZ, 2021)

In Indonesia, emission standards follow the cement plant emission standards which utilise RDF, as stipulated by the Minister of Environment and Forestry Regulation No. P.19/MENLHK/SETJEN/KUM.1/2/2017. In contrast, Germany's emission standards are aligned with stricter limit values set by the 17th BImSchV, which regulates exhaust emissions from mono-waste incineration plants and waste co-incineration in plants involved in the production of cement clinker or cement. The standards established in Germany are more stringent compared to the European Union’s 2010/75/EU, issued by the European Parliament and the Council on 24 November 2010, concerning industrial emissions (integrated pollution prevention and control)[1].

To maintain compliance with environmental regulations, the cement industry must adopt effective emission control measures to ensure that air emissions remain below the applicable

[1] An interim accord was established on November 29, 2023, to reduce the threshold. However, as of now, there have been no further developments regarding amendments to the directive number set to commence in 2030, nor on the initiation of electronic permitting systems by 2035. This accord was formally ratified by the European Union Parliament and Council in March and April of 2024, respectively.

standard limits. The best practices for emission reduction techniques, according to Holcim & GIZ (2020), are as follows:

- Managing diffuse dust: implement coverage for large storage zones and heaps, incorporate barriers against wind for open piles, apply water sprays and chemical agents for dust suppression, facilitate hard-surfaced paving, maintain moisture on roads, and conduct diligent cleaning practices.
- Controlling channelled dust: utilise electrostatic precipitators, employ fabric/bag filters and hybrid filters. The bag filter is currently the best solution due to its high efficiency in dust removal.
- Reducing volatile organic and odour-causing compounds: utilise adsorption techniques, biological filtration, thermal incineration, and wet scrubbing processes.
- Mitigating SO_2 emissions: improve the milling process of raw materials, apply adsorption strategies, and enforce wet scrubbing techniques.
- Curtailing NOx emissions: implement primary strategies such as cooling flames, installing low NOx burners, and optimising processes, adopt staged combustion (using conventional fuels or alternative fuels).
- Decreasing CO, Total Volatile Organic Compounds (TVOC), and benzene: optimise the combustion sequence, and prevent the introduction of materials high in VOC through the raw material feed system.
- Reducing HCl and HF emission: integrate techniques such as filter dust removal, employ Cl gas bypass systems, and use adsorption methods.
- Managing NH_3: optimise to reduce residual ammonia emanating from incomplete reactions in the NOx reduction process via SNCR.
- Preventing PCDD/F formation: exercise discretion in the selection and control of input substances (such as Cl, Cu, and volatile organic compounds in raw materials and fuels), restrict the use of AFs containing chlorinated organics, and avoid processing during the preliminary and concluding stages of kiln operation. Given the propensity for dioxins and furans to form between 250–450°C through surface-assisted reactions or spontaneous synthesis, it is vital to swiftly cool exit gases below 200°C. Modern preheater and precalciner kilns typically incorporate this design element.
- Controlling heavy metal emissions: limit the presence of these metals in input materials and use effective dust removal methods. To assure compliance with regulatory limits, a routine analysis of the heavy metal content in materials used for the cement kiln is necessary.

8.2 Special Features of Indocement Citeureup Plant

As a realisation of the company's commitment to go beyond compliance with regulations and meet the targets set by Heidelberg Material, Indocement's Citeureup factory has implemented policies to reduce emissions by 2025. The policies are aimed to limit dust emissions to 10 mg/Nm³ and achieve 300 mg/Nm³ for NOx and SO_2. To attain these goals, the company has executed the following actions:

- Monitoring levels of SO_2, NO_x, and particulate matter using a continuous emission monitoring system (CEMS) that is connected online with the Ministry of Environment and Forestry.
- Implementing external calibration of CEMS using the Cylinder Gas Audit (CGA) method to ensure the accuracy of CEMS readings.
- The transformation of electrostatic precipitators (EP) into bag filters at 5 out of 10 plants has been carried out progressively by the company since 2015. The bag filter is highly effective in dust reduction, achieving efficiencies greater than 99% (Schiller & Schmid, 2015). The optimisation of the bag filters implemented across plants 4, 5, 8, 11, and 14 has succeeded in reducing dust emissions by achieving an average dust level of < 10 mg/Nm^3. Thus, the company continues to install bag filters gradually at other plants.

Figure 8. 2 Bag filter (right) and CEMS (left)
(Indocement, 2023b)

Figure 8.2 illustrates an example of a bag filter and CEMS equipment installed at the Indocement Citeureup plant. The figure provides a visual reference for the equipment used in emissions management.

Additionally, Table 8.2 below details the types of emission monitoring and the frequency of sample collection. Due to the environmental impact of cement dust on soil, annual soil checks in dust fall centres are advised. The dust's high calcium and alkalinity alter soil properties and increase pH near cement plants (Lamare & Singh, 2020).

Tabel 8. 2 Emission Monitoring and Sampling Frequency

Monitoring Type	Location	Parameters	Monitoring Frequency
Stack emission monitoring	Kiln	SO_2, NO_X, and dust	CEMS
	Kiln, coal mill, cooler, finish mill and packing	SO_2, NO_X, dust, HF, HCL, CO, TOC, and heavy metals	Every 6 months
	Kiln	Dioxin & furans	Every 5 years
Ambient monitoring	Around nearby village	SO_2, NO_X, dust, CO, O_3, NH_3, H_2S and Pb	Every 6 months
Air sampler dust	Plant and office	particulate matters	Every 6 months
Personal dust sampler	Workers	particulate matters	Every 6 months
Dust fall	55 points located 2.5 kilometers from the cement plant	dust	Monthly

Table 8.3 presents the average annual results of CEMS installations, reflecting the outcomes of Indocement's emissions management policies. These results highlight the environmental impacts and demonstrate compliance with sustainability standards and regulations. Based on the table, SO_2 levels dropped from 565.6 in 2018 to 291.9 in 2023, NOx levels reduced from 531.3 to 249.2, and dust emissions decreased from 39.6 to 6.6. All parameters were within Indonesian standards, indicating a consistent emission reduction trend.

Tabel 8. 3 The Average Results of the Main Emission Parameter Measurements

Parameters	Unit	Indonesia Standard Limit	2018	2019	2020	2021	2022	2023
SO_2	mg/Nm3	650	565.6	486.0	405.0	314.5	343.4	291.9
NO_x	mg/Nm3	800	531.3	524.0	566.0	226.7	234.9	249.2
Dust	mg/Nm3	60	39.6	58.0	46.0	16.8	8.4	6.6

An example of the operational conditions and emission measurement results from one of Indocement's plants in Citeureup, plant (kiln) 14, is displayed in Table 8.4. With a design clinker production capacity of 4.4 million Mg per year, this plant produced 3.4 million Mg in 2023. The details of the actual production conditions of plant 14 are also shown in Table 8.4.

Tabel 8. 4 Material and Fuel Conditions in Plant 14

Material	Mg/year	Mg/day	Material	Mg/year	Mg/day
Raw Mill Input			**Cement mill**		
Laterite	10,497	32	Clinker	3,083,020	9,342
Alternative material	133,380	404	Limestone	848,997	2,573
Sandy clay/clay	682,495	2,068	Pozzolanic	30,175	91
Limestone	4,846,306	14,686	GBFS	70,240	213
Copper slag	35,194	107	Gypsum	141,634	429
Iron concentrate	3,946	12	Fly ash	12,610	38
Trass	14,151	43	Trass	406,307	1,231
Total	5,725,969	17,351	Total	4,592,983	13,918
Kiln			**Fuel**		
Raw meal input	5,542,670	16,796	Fine coal	396,596	1,202
Clinker produced	3,442,688	10,432	Mixed alternative fuel	38,631	117
			RDF	13,321	40
			Mixed biomass	74,138	225
			Fuller's earth	7,723	23
			Tire	5,629	17
			Total	536,037	1,624

(Indocement, 2023a)

In 2023, the plant processed 5.7 million Mg of raw mill input into 5.5 million Mg of kiln raw meal, resulting in the production of 3.4 million Mg of clinker. Within the raw mill input, the alternative material consisted of bottom and fly ash. The cement mill produced 4.6 million Mg of cement. AFs accounted for 17.9% of the thermal energy used, utilising 139,442 Mg. The mixed AF comprised 39% industrial waste oil, 39% rubber, and approximately 22% textile waste. Meanwhile, RDF originated from MSW in Jakarta and commercial areas. The mixed biomass came from 70% woodchips and 30% sawdust. Fuller's earth is bentonite that has been used in the bleaching process from the palm oil refinery. Tires came from used cars and trucks.

Tabel 8. 5 Emission Report Plant 14 in 2023

No	Parameter	Unit	Average measurement			Standard limit	
			Plant 14		Germany Cement Plant	Indonesia	Germany
			2023	Data Count			
1	Total particulate matter/dust	mg/Nm^3	4.88[1]	CEMS	1-10[4,5]	60[1,2]	10[3,4]
2	SO_2	mg/Nm^3	44.78[1]	CEMS	5-120[4,5]	650[1,2]	50[3,4]
3	NOx	mg/Nm^3	250.28[1]	CEMS	100-220[4,5]	800[1,2]	200[3,4]
4	HCl	mg/Nm^3	3.45[1]	2	1-15[4,5]	20[1,2]	10[3,4]
5	Hg	mg/Nm^3	0.046[1]	2	0.013- 0.022[3]	0.2[1,2]	0.03[3,4]
6	CO	mg/Nm^3	193.04[1]	2	10-50[4,5]	625[1,2]	50[3,4]
7	HF	mg/Nm^3	<0.014[1]	2	<0.5[4,5]	2[1,2]	1[3,4]
8	Cd	mg/Nm^3	0.0067[1]	2	< 0.01-0.02[4,5]	0.2[1,2]	Cd limit is combined with Tl as Cd+Tl
9	Cd+Tl	mg/Nm^3	0.00719[1]	2	<0.05[4,5]	-	0.05[4]
10	Pb	mg/Nm^3	0.0242[1]	2	<0.04[4,5]	5[1,2]	These heavy metal parameters are combined as shown in number 16
11	As	mg/Nm^3	0.0002[1]	2	< 0.005[4,5]	1[1,2]	
12	Ni	mg/Nm^3	0.0296[1]	2	< 0.02[4,5]	0.5[1,2]	
13	Cr	mg/Nm^3	0.0011[1]	2	< 0.01[4,5]	-	
14	Cu	mg/Nm^3	0.0002[1]	2	<0.05[4,5]	-	
15	TOC	mg/Nm^3	12.06[1]	2	1-5[4,5]	100[1,2]	10[3,5]
16	Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V+Sn	mg/Nm^3	0.0575[1]	2	<0.5[4,5]	-	0.5[5]
17	Carcinogenic substances (As,BaP,Cd, Co, and Cr)	mg/Nm^3	-	-	<0.05[4,5]	-	0.05[5]
18	NH_3	mg/Nm^3	24.78[1]	2	5-35[4,5]	-	30[3,5]
19	PCDD/F (dioxin and furan)	ng TEQ/Nm^3	0.0033[1]	1	<0.005[4,5]	0.1[1,2]	0.1[3,5]

([1]Indocement, 2023a; [2]KLHK, 2017; [3]Lahl et al., 2020; [4]VDZ, 2018; [5]VDZ, 2021)

The emission data from the plant can be found in Table 8.5. Based on the above table, all parameters met the Indonesian standard limits. However, parameters such as NOx, CO, and TOC that exceeded the limit of the German standards. This is due to incomplete combustion, either from the production process operations or the quality of the fuel used (Öztürk et al., 2022).

8.3 Pollutant Analysis in Plant 14: Current Status

An analysis of the pollutant load was undertaken, with a focus on air emissions. To complement this, calculations were also performed on the material input and output for the cement product. These analyses were conducted for selected parameters, including Cl, Cd, Pb, Cr, Hg, and TOC. Additional parameters for air emissions were HCl and PCDD/F. The air emission pollutant load can be found in Table 8.6 below.

Tabel 8. 6 Average of Selected Air Emission Pollutant Parameter Emission in Plant 14 in 2023

Unit	Dust	HCL	Cl	PCDD/F	Cd	Pb	Cr	Ni	Cu	Hg	TOC
mg/Nm^3	4.88	3.45	3.36	0.0033 ng TEQ/Nm^3	0.0067	0.0242	0.0011	0.0296	0.0002	0.046	12.06
g/hour	3,215	2,273	2,211	2714 ng/hour	4.41	15.94	0.72	19.50	0.13	30.31	7,946

(Indocement, 2023a)

In the previous table, the selected air emission condition in 2023 at Plant 14 with the use of AF with a heat substitution of 17.9%. The mass produced was measured in g/hour, obtained by considering an air volume of 658,873 Nm^3/hour (Indocement, 2023a). The mass of Cl was derived from calculations using the atomic mass ratio from HCl. Figure 8.3 below illustrates the mass flow in the cement production process.

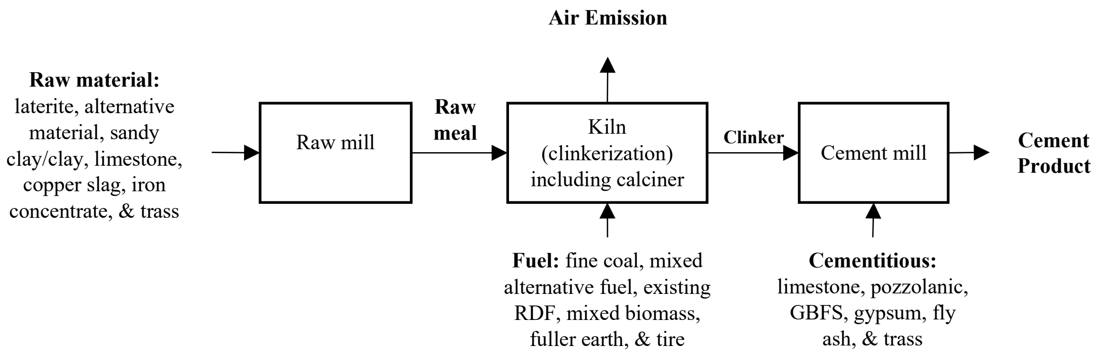

Figure 8. 3 Mass Flow in the Cement Production Process

To determine the pollutant load for material input and output, the concentrations of pollutants is presented in Table 8.7 below. The table provides detailed measurements for various materials, including raw mill inputs, fuel inputs, and clinkerization outputs.

Tabel 8. 7 Selected Pollutants Concentration in Input & Output Material at Plant 14 in 2023

Material Name	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	% wt. (db.)	mg/kg (db.)						% wt. (db.)
Raw Mill Input								
Laterite	0.01	4.2	52.1	21.1	22.0	210.9	0.16	0.25
Alternative material	0.01	4.3	77.2	30.2	65.7	120.6	0.28	1.20
Sandy clay/clay	0.01	0.3	44.9	25.2	36.1	48.1	0.16	0.04
Limestone	0.01	0.2	2.9	17.8	7.0	19.0	0.09	0.04
Copper slag	0.01	1.7	59.1	21.1	44.2	3331.2	0.19	0.03
Iron concentrate	0.01	4.5	162.0	89.2	18.9	612.0	0.10	0.20
Trass	0.01	0.76	30.1	14.0	43.1	31.3	0.07	0.09

Table 8.7 Selected Pollutants Concentration in Input & Output Material at Plant 14 in 2023 (continue)

Material Name	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	% wt. (db.)	mg/kg (db.)						% wt. (db.)
Fuel Input								
Fine coal	0.01	2.0	2.1	1.0	2.0	3.2	0.17	53.9
Mixed alternative fuel	0.08	7.8	5.0	34.2	15.1	7.9	0.27	69.7
RDF	0.42	7.6	14.0	10.1	17.0	29.0	0.33	46.0
Mixed biomass	0.01	1.7	12.0	6.2	74.3	51.1	0.26	68.1
Fuller earth	0.01	2.8	12.0	2.9	65.0	42.0	0.27	32.0
Tyre	0.01	6.6	7.0	1.9	12.1	33.1	0.24	60.9
Clinkerization Output								
Clinker	0.02	0.9	17.7	32.5	22.4	78.6	0.10	0.05
Cement Mill								
Clinker	0.02	0.9	17.7	32.5	22.4	78.6	0.10	0.05
Limestone	0.01	0.2	2.9	17.8	7.0	19.0	0.09	0.06
Pozzolanic	0.01	3.0	4.1	1.0	14.0	11.0	0.03	0.07
GBFS	0.01	2.0	1.0	6.0	45.1	38.0	0.01	0.06
Gypsum	0.01	2.0	2.1	3.1	13.2	8.0	0.01	0.10
Fly ash	0.01	3.0	47.0	2.0	27.8	59.0	0.02	1.20
Trass	0.01	0.8	30.1	14.0	43.1	31.3	0.02	0.06
Total	0.02	0.9	14.0	32.0	19.0	52.0	0.09	0.05

(Indocement, 2023a)

Table 8.8 below presents a comparison of the concentration of selected pollutants in cement produced at Plant 14 with that of typical cement from several references. The table indicates differences in the parameters of Cd, which was above the typical cement levels. Meanwhile, Cu concentration was significantly below the typical cement levels. These discrepancies are highly likely due to variations in input materials. This aligns with the investigation of Ogunbileje et al. (2013), which also revealed differences in heavy metal concentrations of cement produced in the USA and Nigeria.

Meanwhile, one of the reasons why TOC is found in cement is that the raw materials used in clinker production are natural sources of TOC that enter the kiln. Furthermore, the specific kiln design, temperature, and residence time influence TOC survival (Shimadzu, 2005).

Tabel 8. 8 Comparison of Selected Pollutants in Plant 14 with Standard Cement Quality

Source	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	% wt. (db.)	mg/kg (db.)						% wt. (db.)
Plant 14	0.02	0.9	14	32	19	52	0.09	0.05
Typical	0.05 - 0.20[1,2]	0.70-7.00[4]	20-45[4]	40-63[4]	15-50[4]	90-100[4]	0.016-0.200[4]	0.04-0.200[3]

([1]Al-Saleh, 2015; [2]Kara et al., 2011; [3]Shimadzu, 2005; [4]VDZ, 2018; [5]VDZ, 2021)

After determining the concentration of each pollutant, it was possible to calculate the respective pollutant load based on the mass of the individual materials. This calculation provided a clear understanding of the pollutant levels. The detailed results are presented on the following page in Table 8.9.

Tabel 8. 9 Selected Pollutants Load in Input & Output Material

Material Name	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	g/hour							
Raw Mill Input								
Laterite	119	5	62	25	26	252	0.19	2,982
Alternative material	1,516	65	1,170	457	996	1,828	4.18	181,881
Sandy clay/clay	7,756	23	3,482	1,954	2,800	3,730	12.10	31,022
Limestone	27,536	110	1,597	9,803	3,855	10,464	51.22	220,287
Copper slag	200	7	236	84	177	13,323	0.77	1,200
Iron concentrate	36	2	73	40	8	274	0.05	897
Trass	113	1	48	23	69	50	0.11	1,447
Total	37,275	214	6,669	12,386	7,931	29,921	68.60	439,717
Fuel Input								
Fine coal	3,005	100	105	50	100	160	8.41	26,990,533
Mixed alternative fuel	3,161	30	20	133	59	31	1.04	2,719,778
RDF	5,678	10	19	14	23	39	0.44	618,933
Mixed biomass	674	13	90	46	556	383	1.95	5,099,764
Fuller earth	78	2	9	2	51	33	0.21	249,644
Tyre	64	5	5	1	9	24	0.17	432,799
Total	12,659	160	248	247	798	669	12.24	36,111,452
Total input in Clinkerization	49,934	374	6,917	12,634	8,729	30,590	80.84	36,551,169
Clinkerization Output								
Clinker	86,937	413	7,703	14,106	9,725	34,158	43.03	217,341
Cement Mill								
Clinker	77,854	369	6,898	12,633	8,709	30,590	38.5	194,635
Limestone	5,360	21	311	1,908	750	2,037	10.0	64,318
Pozzolanic	191	11	16	4	53	42	0.1	2,667
GBFS	621	18	9	53	400	337	0.1	5,321
Gypsyum	1,073	36	38	55	236	143	0.2	17,883
Fly ash	96	5	75	3	44	94	0.03	19,106
Trass	3,591	39	1,544	718	2,211	1,606	1.2	30,781
Total	38,180	500	8,890	15,375	12,404	34,848	50.17	334,711
Emission	2,211	4.41	15.94	0.72	19.50	0.13	30.31	7,946

There were two sources of Cl within the kiln system: one from the material input and the other from previously circulated Cl. The clinker would absorb these sources to a maximum of 3.3% for kilns without a Cl bypass and 3.1% for kilns with a Cl bypass (Zhan et al., 2016). As an example, in Table 8.9, where the clinker load is 86,937 g/hour while the material input is only 49,934 g/hour. This discrepancy is due to the clinker also absorbing Cl from previously circulated chlorine. The amount circulated was 4,129,009 g/hour, derived from the Cl content in hotmeal Plant 14 in 2023, averaging 0.49% wt. (db.) for an average rate of 700 Mg/hour.

Thus, the total Cl burden on the kiln system was 4,178,943 g/hour. Consequently, the clinker absorbed 2.1% of the total Cl in the kiln system. The typical Cl content in clinker ranged from 0.01% to 0.15% % wt. (db.). If the kiln is no longer able to maintain the Cl level in the clinker (has exceeded its value range), it is recommended to install a Cl bypass in the kiln system (Al-Saleh, 2015; Pisch, 2015). In plant 14, the Cl level in the clinker was 0.02% wt. (ab), indicating that there is no need to install the bypass system.

In general, the clinkerization process is notably efficient at integrating heavy metals into a monolithic compound, thereby diminishing their volatilization into the atmosphere (Fzka et al., 2003). However, this does not apply to mercury (Hg). Mercury is not as effectively absorbed by the clinker due to its volatile nature, with an average of approximately 38-40% of the total mercury input load being released into the air (VDZ, 2018). In the data presented in Table 8.9, around 37% of mercury is estimated to be released into the air, which amounts to 30.31 g/h compared to the input of 80.84 g/h. Regarding TOC, the rotary kiln excelled in decomposing it into simpler compounds such as CO_2, owing to the high temperatures and negative pressure within the kiln, coupled with the employment of a bag filter. To enhance TOC emission mitigation, it is crucial to ensure stable kiln processes and optimising the bag filter system (Bujak et al., 2021). In plant 14, the capability for TOC destruction was 99.9%, with a TOC reduction amounting to 36,543,223 grams per hour from an input value of 36,551,169 grams per hour, or an emission factor of 0.022% for TOC.

8.4 Pollutant Load from RDF Modelling

The analysis of pollutant loads incorporates data on heavy metals from strategy 3, which is part of the RDF pilot project, as detailed in Table 6.11. The data was taken from a total of 10 measurements from 10 trials that had been carried out, except for the TOC data. The TOC data was obtained from five samples taken from actual RDF incoming in 2024. Meanwhile, the average mercury concentration was determined to be 0.29 mg/kg based on the figure provided by VDZ, (2018).

Tabel 8. 10 Pollutant Concentrations of RDF Modelling

Parameters	Unit	RDF	Low-grade RDF	Worst Case	Europe Class 3 & Germany	Indonesia
Cl	% wt. (db.)	0.49 ± 0.02	0.52 ± 0.04	1.0	≤1.0[1]	≤0.75[2]
Cd	mg/kg (db.)	9 ± 1	9 ± 1	22	≤9[3]	≤70[2]
Pb		14 ± 1	14 ± 1	91	≤200-400[4]	≤100[2]
Cr		13 ± 1	13 ± 1	70	≤120-250[4]	≤1500[2]
Ni		15 ± 1	16 ± 1	64	≤100[4]	≤1000[2]
Cu		35 ± 4	32 ± 3	115	≤300-700[4]	≤1000[2]
Hg		0.29 ± 0.01	0.29 ± 0.01	0.46[5]	<1.2[4]	<1.2[2]
TOC	% wt. (db.)	54 ± 2	40 ± 2	57.5[3]	-	-

([1]CEN, 2021a; [2]Kemenperin, 2017; [3]Lechtenberg & Partner, 2008; [4]MUNLV, 2005; [5]VDZ, 2018)

The comparative data of pollutant concentrations can be found in Table 8.10. In the table, the worst-case scenario column presents Cl, Cd, Pb, Cr, Ni, and Cu data obtained from the maximum values in the typical RDF quality from Table 6.13. The value for Hg at 0.46 mg/kg (db.) was based on data from VDZ (2018), while the TOC content of 57.5% wt. (db.) was based on a report by Lechtenberg & Partner (2008).

The RDF pollutant concentrations met the Indonesian pollutant standards. Cd in RDF could reach a maximum concentration of 10 mg/kg (db.), exceeding the German standard of 9 mg/kg (db.). The analysis evaluated the extra pollutant load from using RDF at Plant 14, targeting a

50% thermal substitution. In 2023, the plant needed 11,008 TJ of energy and achieved a 17.9% thermal substitution (1,970 TJ) using 139,441 Mg of AF with an average LHV of 14.1 MJ/kg. An additional 32.1% energy (3,534 TJ) was required. The RDFP-3 model required 432 Mg/day per RDF variant, totalling 864 Mg/day. For an 80% thermal substitution, RDF must contribute 62.1%, generating 6839 TJ, which equates to 835 Mg/day per RDF type, or a total of 1670 Mg/day.

Table 8. 11 Additional Pollutant Load from RDF Utilisation Based on Modelling Results

Parameters	Unit	50% AF Substitution			80% AF Substitution		
		RDF	Low-grade RDF	Total	RDF	Low-grade RDF	Total
Mass	Mg/day	432	432	864	835	835	1,670
Moisture	% wt. (ar.)	25	42	67	25	42	67
Dry mass	Mg/hour	14	10	24	26	20	46
Ash	Mg/hour	3	2	4	5	3	9
Cl	g/hour	65,475	53,766	119,241	126,555	103,923	230,477
Cd		135	94	229	261	182	443
Pb		189	146	335	365	283	648
Cr		176	136	311	339	262	602
Ni		203	167	370	391	323	714
Cu		473	334	807	913	646	1,559
Hg		3.96	3.06	7.01	7.65	5.91	13.56
TOC		7,227,155	4,140,000	11,367,155	13,969,154	8,002,083	21,971,237

Table 8.11 shows the additional pollutant load from RDF utilisation based on modelling results. The table also contains a load of ash originating from the RDFP-3 modelling detailed in Table 7.14. This data is valuable for determining the increase in clinker quantity when utilising the output from that model. The pollutant load calculation was obtained by multiplying the RDF dry mass by the pollutant concentration in Table 8.10 and the ash content in Table 7.14.

8.5 Evaluation of Potential Pollutant Load

The evaluation of the pollutant load for plant 14 has been conducted using four scenarios[2]. Scenario 1 was without AF, while scenario 2 applied existing AF with a thermal substitution of 17.9%. Scenario 3 incorporated the use of AF with a 50% thermal substitution, a 32.1% contribution from the modelled RDF, and the installation of a Cl bypass. Lastly, scenario 4 involved the use of AF with an 80% thermal substitution, a 62.1% contribution from the modelled RDF[2], and the installation of a Cl bypass. The installation of the Cl bypass aimed to

[2] The thermal energy requirement for plant 14 was 11,008 TJ in 2023. In scenario 1, no alternative fuel was used. Scenario 2 used the existing 17.9% of thermal energy from 2023, which was around 1970 TJ. Scenario 3 incorporated the thermal substitution of 50% (5504 TJ), 17.9% from existing AF, and an additional 32.1% from modelled RDF. Scenario 4 involved a thermal substitution of 80%, with an additional 62.1% from modelled RDF adding to the existing 17.9%, making the total substitution of 8806 TJ.

reduce the impact of Cl circulation due AF utilisation on the cement process, products, and emissions (Zhan et al., 2016). For the modelling calculations, an emission factor that explained the emitted portion of the total load input was required. This emission factor explained the quantification of how much % load of the input was emitted into the air. Emission factors were obtained from several references, as summarized by Table 8.12.

Tabel 8. 12 Emission Factors in Percentage for Rotary Kiln Systems

Kiln Type	**Cl**	**Cd**	**Pb**	**Cr**	**Ni**	**Cu**	**Hg**	**TOC**
Kiln without Cl bypass	14.50[2]	0.17[1]	0.05[1]	0.01[1]	0.03[1]	0.01[1]	40.00[1]	0.022[1]
Kiln with Cl bypass	10.91[2]							

([1]VDZ, 2021; [2]Zhan et al., 2016)

The transfer coefficient of Cl to clinker (quantification of the % load of Cl from the total input transferred to the clinker) was used from the total Cl in the kiln system, which consisted of input material sources and circulated Cl assumed to be fixed at 4,178,943 grams per hour. The transfer coefficient was 3.3% for kilns without a Cl bypass and 3.1% for kilns with a Cl bypass (Zhan et al., 2016).

Based on Table 8.12, only the TOC values that were based from this research, which were obtained from the performance at plant 14. For comparison, the TOC emission factor from other study was 0.049% of the input portion (Sładeczek & Głodek, 2015). Additionally, according to research by (Vidlička et al. 2022), the emission factor was less than 0.01% because the installation of a bag filter might reduce TOC emissions from 82.6 mg/Nm^3 to 8.4 mg/Nm^3.

Tabel 8. 13 Pollutants Load of Each Scenario

Material Name	**Mass**	**Cl**	**Cd**	**Pb**	**Cr**	**Ni**	**Cu**	**Hg**	**TOC**
	Mg/hour	**g/hour**							
Scenario 1: Without AF									
Raw-material input	723	37,275	214	6,669	12,386	7,931	29,921	69	439,717
Fuel in clinkerization									
Fine coal	61	3,294	110	115	55	110	176	9.2	29,587,673
Existing AF	-	-	-	-	-	-	-	-	-
RDFP-3 product	-	-	-	-	-	-	-	-	-
Total	61	3,294	110	115	55	110	176	9.2	29,587,673
Kiln system									
Total input in the clinkerization	784	40,568	323	6,784	12,441	8,041	30,097	78	30,027,390
Circulated in kiln system	-	4,129,009	-	-	-	-	-	-	-
Total	784	4,169,577	323	6,784	12,441	8,041	30,097	78	30,027,390
Total in clinker	434	137,596	323	6,784	12,441	8,041	30,097	47	183,167
Total in cement	580	134,432	453	8,776	15,183	11,736	34,355	58	323,243
Emission		478	0.19	0.06	0.01	0.03	0.02	31	6,432
Scenario 2: With Existing AF									
Raw-material input	723	37,275	214	6,669	12,386	7,931	29,921	69	439,717
Fuel in clinkerization									
Fine coal	50	3,005	100	105	50	100	160	8.4	26,990,533
Existing AF	18	9,655	60	143	197	698	509	3.8	9,120,919
RDFP-3 product	-	-	-	-	-	-	-	-	-
Total	68	12,659	160	248	247	798	669	12.2	36,111,452
Kiln system									
Total input in the clinkerization	791	49,934	374	6,917	12,634	8,729	30,590	81	36,551,169
Circulated in kiln system	-	4,129,009	-	-	-	-	-	-	-
Total	791	4,178,943	374	6,917	12,634	8,729	30,590	81	36,551,169
Total in clinker	435	137,905	373	6,913	12,632	8,726	30,587	49	222,962
Total in cement	580	134,429	504	8,905	15,374	12,422	34,846	60	363,038
Emission		7,240	0.64	3.46	1.52	2.62	2.84	32	7,946

Table 8. 13 Pollutants Load of Each Scenario (continue)

Material Name	Mass	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	Mg/hour	g/hour							
Scenario 3: 50% AF Substitution & Cl bypass									
Raw-material input	723	37,275	214	6,669	12,386	7,931	29,921	69	439,717
Fuel in clinkerization									
Fine coal	30	1,830	61	64	30	61	98	5	16,437,596
Existing AF	18	9,655	60	143	197	698	509	4	9,120,919
RDFP-3 product	36	119,241	229	335	311	391	807	7	11,367,155
Total	84	130,725	350	542	539	1,150	1,413	16	36,925,670
Kiln system									
Total input in the clinkerization	807	168,000	564	7,211	12,925	9,081	31,334	85	37,365,387
Circulated in kiln system	-	4,129,009	-	-	-	-	-	-	-
Total	807	4,297,009	564	7,211	12,925	9,081	31,334	85	37,365,387
Total in clinker	439	133,207	563	7,207	12,924	9,079	31,331	51	227,928.86
Total in cement	580	129,006	693	9,199	15,666	12,774	35,589	62	368,005
Emission		24,360	0.96	3.61	1.55	2.72	2.91	34	8,123
Scenario 4: 80% AF Substitution & Cl bypass									
Raw-material input	723	37,275	214	6,669	12,386	7,931	29,921	69	439,717
Fuel in clinkerization									
Fine coal	12	732	24	26	12	24	39	2	6,575,039
Existing AF	18	9,655	60	143	197	698	509	4	9,120,919
RDFP-3 product	70	230,477	443	648	602	714	1,559	14	21,971,237
Total	99	240,864	527	816	811	1,436	2,107	19	37,667,195
Kiln system									
Total input in the clinkerization	822	278,139	741	7,485	13,197	9,368	32,028	88	38,106,911
Circulated in kiln system	-	4,129,009	-	-	-	-	-	-	-
Total	822	4,407,148	741	7,485	13,197	9,368	32,028	88	38,106,911
Total in clinker	443	136,622	740	7,481	13,196	9,365	32,025	53	232,452
Total in cement	580	130,892	870	9,473	15,938	13,060	36,283	64	372,528
Emission		40,330	1.26	3.74	1.58	2.81	2.98	35	8,284

Table 8.13 indicates each pollutant's potential load, accounting for the clinker mass increase from RDFP-3 ash content. Additionally, the load was influenced by the increased RDF consumption, which has the potential to reduce coal consumption. This is because coal generally has a lower pollutant concentration compared to RDF. Another approach that was applied was assuming that the cement's composition remained the same as the actual conditions in 2023, as indicated in Table 8.14. The calculated pollutant concentrations for materials were compared with typical clinker and cement values, highlighting changes from using RDF. These details are presented in Table 8.14 below, which also indicates that the pollutant concentration in both the clinker and cement scenarios aligns with typical levels.

Table 8. 14 Pollutants Concentration of Each Scenario

Material Name	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	% wt. (db.)	mg/kg (db.)						% wt. (db.)
Scenario 1: Without AF								
Clinker	0.03	0.7	15.6	28.7	18.5	69.4	0.11	0.04
Cement	0.02	0.8	15.1	26.2	20.2	59.2	0.10	0.06
Scenario 2: With Existing AF								
Clinker	0.03	0.86	15.90	29.06	20.08	70.37	0.11	0.05
Cement	0.02	0.87	15.36	26.51	21.42	60.09	0.10	0.06
Scenario 3: 50% AF Substitution & Cl bypass								
Clinker	0.03	1.28	16.41	29.43	20.67	71.34	0.12	0.05
Cement	0.02	1.20	15.86	27.01	22.03	61.37	0.11	0.06
Scenario 4: 80% AF Substitution & Cl bypass								
Clinker	0.03	1.67	16.88	29.76	21.12	72.24	0.12	0.05
Cement	0.02	1.50	16.34	27.48	22.52	62.57	0.11	0.06
Typical Concentration								
Clinker	0.01-0.15[1,4]	0.50-7.00[2,8]	2-38[2,8]	20-100[8]	20-50[8]	24-100[8]	0.010-0.200[7]	0.05-0.200[6]
Cement	0.05 - 0.20[1,34]	0.70-7.008	20-458	40-63[8]	15-50[8]	90-100[8]	0.016-0.200[7]	0.04-0.200[5]

([1]Al-Saleh, 2015; [2]Huang et al., 2021; [3]Kara et al., 2011; [4]Pisch, 2015; [5]Shimadzu, 2005; [6]Sładeczek & Głodek, 2015; [7]VDZ, 2018; [8]VDZ, 2021)

In the subsequent section, Table 8.15 presents detailed air emission results for each scenario, calculated using emission loads from Table 8.13, factors from Table 8.12, and a flue gas volume of 658,873 Nm³/h. It also incorporates actual data from 2023, aligning with Table 8.6, and systematically compares these results to emission standards in Indonesia and Germany.

Table 8. 15 Potential Air Emission of Each Scenario in Plant 14

Scenario	PCDD/PCDF	HCL	Cl	Cd	Pb	Cr	Ni	Cu	Hg	TOC
	ng TEQ/Nm³	mg/Nm³								
Scenario 1: Without AF	0.001*	0.2	0.2	0.001	0.005	0.001	0.001	0.001	0.047	9.8
Scenario 2: With existing AF	0.003	3.4	3.4	0.001	0.005	0.002	0.004	0.004	0.049	12.1
Scenario 3: 50% AF substitution & Cl bypass	0.017	11.6	11.3	0.001	0.005	0.002	0.004	0.004	0.051	12.3
Scenario 4: 80% AF substitution & Cl bypass	0.028	19.2	18.7	0.002	0.005	0.002	0.004	0.005	0.053	12.6
Actual emission in 2023	0.003	3.4	3.4	0.007	0.02	0.001	0.003	<0.001	0.046	12.1
Indonesia emission standard	0.1	20.0	-	0.2	5	-	0.5	-	0.20	100.0
Germany emission standard	0.1	10.00	-	as Cd+Tl = 0.05	-	-	-	-	0.03	10.0

*Based on actual figure from 2020 when using only 8 Mg/day of alternative fuel

It should be noted that there is a significant correlation between Cl concentration and the emissions of dioxins and furans (PCDD/PCDF). According to Costner (2001), a twofold increase in Cl input might result in a threefold rise in dioxin and furan emissions, reflecting a linear relationship in emission calculations. For instance, referring to Table 8.13, the Cl input in scenario 3 was 168,000 g/hour, whereas, in scenario 2, which represented the existing condition in 2023, it was 49,934 g/hour. In scenario 3, there was an increase in input by a factor of 3.34 times, resulting in an emission increase by a factor of 5 compared to scenario 2—from 0.003 ng/Nm³ in scenario 2 to 0.017 mg/Nm³ in scenario 3.

Subsequently, a stoichiometric comparison with Cl was utilised for HCl emissions. The Cl emission calculation not only considered the emission factors in Table 8.12 but also considered the current existing conditions, where plant 14 implemented a scrubbing process with CaO. If plant 14 only depends on the emission factor, then in the scenario 2 calculation, Cl emission will be 11.0 mg/Nm³. In contrast, the actual measurement result was 3.4 mg/Nm³, accounting for 30.5% of the calculation prediction. In all scenarios applied, the Cl emission output would be multiplied by a factor of 30.5%. Conversely, another study by Pachitsas et al., (2019) indicated that the same scrubber system achieved up to a 0.04% portion factor. The emission levels complied with Indonesian standards, allowing RDF utilisation. However, under German regulations, HCl, Hg, and TOC emissions approached the limits. To address this, the cement plant needs to upgrade the HCl scrubbing system, install a mercury capture system to reduce Hg emissions, and improve bag filters for TOC reduction.

Table 8.16 presents the model results for calculating potential pollutants in products and emissions for Scenarios 3 and 4. These calculations were based on the worst-case figures for each pollutant, considering both RDF and low-grade RDF, as outlined in Table 8.10. The methodology applied here aligns with those used in Tables 8.14 and 8.15. Additionally, Table 8.16 provides details on the worst-case pollutant concentration in clinker and cement and also reveals a substantial increase in heavy metals across all scenarios. However, the concentration of pollutants in clinker and cement remained within the typical range.

Table 8. 16 Worst Case Pollutants Concentration of Scenarios 3 and 5

Material Name	**Cl**	**Cd**	**Pb**	**Cr**	**Ni**	**Cu**	**Hg**	**TOC**
	% wt. (db.)	**mg/kg (db.)**						**% wt. (db.)**
Scenario 3: 50% AF Substitution & Cl bypass								
Clinker	0.03	1.96	20.61	32.54	23.58	75.78	0.12	0.06
Cement	0.02	1.71	19.04	29.37	24.23	64.73	0.11	0.07
Scenario 4: 80% AF Substitution & Cl bypass								
	% wt. (db.)	**mg/kg (db.)**						**% wt. (db.)**
Clinker	0.03	2.96	24.91	35.71	26.19	80.72	0.13	0.06
Cement	0.02	2.49	22.48	32.03	26.39	69.05	0.12	0.07
Typical Concentration								
Clinker	0.01-0.15	0.50-7.00	2-38	20-100	20-50	24-100	0.010-0.200	0.05-0.200
Cement	0.05 - 0.20	0.70-7.00	20-45	40-63	15-50	90-100	0.016-0.200	0.04-0.200

Table 8.17 below shows the results of the worst-case potential air emissions. The emission calculations indicated that all parameters complied with Indonesian standards, except for HCl in scenario 4. To mitigate this risk, Indocement should consider using input materials with lower Cl levels or implementing an improved HCl scrubbing process. When assessed against Germany's emission limits, the HCL, Hg, and TOC in scenarios 3 and 4 exceeded the allowable thresholds.

Table 8. 17 Worst Case Potential Air Emission of Each Scenario in Plant 14

Scenario	**PCDD/PCDF**	**HCL**	**Cl**	**Cd**	**Pb**	**Cr**	**Ni**	**Cu**	**Hg**	**TOC**
	ng TEQ/Nm^3	mg/Nm^3								
Scenario 3: 50% AF substitution & Cl bypass	0.029	19.9	19.4	0.002	0.007	0.003	0.005	0.005	0.054	13.1
Scenario 4: 80% AF substitution & Cl bypass	0.051	35.3	34.4	0.003	0.008	0.003	0.005	0.005	0.058	14.1
Indonesia emission standard	0.1	20.0	-	0.2	5	-	0.5	-	0.20	100.0
Germany emission standard	0.1	10.00	-	as Cd+Tl = 0.05	-	-	-	-	0.03	10.0

9. Conclusion and Recommendation

Based on the investigation carried out, as discussed in the previous subsection, the conclusions are as follow:

1. The MSW source is not yet suitable for RDF production due to high moisture content (55%) and low LHV (5.4 MJ/kg). However, with 80-90% of the MSW fraction being combustible, further mechanical treatment can make it viable for RDF production.
2. The RDF plant pilot project tested four strategies. Strategy 1 used a 16-day bio-drying process, reducing moisture to 30%. Strategy 2 incorporated solar drying, reducing drying time to 13 days and improving RDF quality. Strategy 3 relied solely on mechanical treatment, resulting in high moisture levels (47-61%) and suboptimal RDF quality. Strategy 4 combined mechanical treatment with a belt dryer, significantly reducing moisture content to 34% and improving RDF quality. Overall, drying processes enhanced RDF quality and energy potential, while mechanical-only methods showed decreased efficiency and product quality. The RDF produced was used by a cement plant. Strategy 1 yielded RDF with the highest LHV of 16.5 MJ/kg, generating 5480 GJ of net energy and reducing CO_2 by 248 Mg. Strategy 2 showed similar performance with an LHV of 16.6 MJ/kg, net energy of 5527 GJ, and CO_2 reduction of 254 Mg. Strategy 3 produced RDF with an LHV of 8.7 MJ/kg, net energy of 3663 GJ, and CO_2 reduction of 174 Mg. Strategy 4 generated RDF with an LHV of 13.1 MJ/kg, net energy of 3478 GJ, and CO_2 reduction of 135 Mg. Strategies 1 and 2 were the most effective, with high RDF quality, energy output, and CO_2 reduction.
3. Four RDF plant designs were modelled, processing 500 Mg/day of MSW. The RDFP-3 model, using drying at the cement plant, was the most cost-effective, with an investment of €1.4/GJ and a payback period of six years. Scaling this model to 13 RDF plants would require €186.8 million in capital and 14.3 hectares of land. Carbon sales (€35/Mg) help reduce the payback period.
4. Achieving a 50% coal substitution rate at the cement plant requires processing 6,500 Mg/day of MSW, resulting in 3,100 Mg/day of RDF. However, 40% of the RDF's composition (plastic fraction) contributes to fossil carbon emissions.
5. 50% AF substitution rate could reduce coal consumption by 608,000 Mg/year and CO_2 emissions by 586,000 Mg/year, representing a 24.2% reduction.
6. Four pollutant load scenarios were evaluated: baseline without AF utilisation (Scenario 1), 17.9% thermal substitution with AF (Scenario 2), 50% thermal substitution with Cl bypass (Scenario 3), and 80% thermal substitution with Cl bypass (Scenario 4). Emissions in all

scenarios complied with Indonesian regulatory thresholds, demonstrating the feasibility of RDF application. However, German standards highlighted exceedances in HCl emissions and near-limit levels for TOC, with heavy metals also identified as concerns. To address these challenges, installing a Cl bypass system is critical for reducing HCl emissions and Cl concentration in clinker, with the added potential to lower Cl content in cement if bypass dust is not reused as an admixture. Enhancing the scrubbing system and optimizing bag filter functionality are also essential for mitigating HCl emissions and TOC levels. Mercury contamination remains a significant issue, as concentrations reached 0.46 mg/kg, surpassing the calculated average of 0.29 mg/kg. Potential mercury emissions increased with AF substitution, rising from 0.047 mg/Nm^3 in Scenario 1 to 0.053 mg/Nm^3 in Scenario 4, and worst-case projections indicated emissions of 0.054 mg/Nm^3 in Scenario 3 and 0.058 mg/Nm^3 in Scenario 4. Systematic and precise emission data recording is crucial for effective project planning, enabling accurate forecasts of potential emissions and ensuring robust environmental control measures.

Recommendation:

1. It is necessary to examine the relationship between sun-drying through a transparent roof and its influence on the bio-drying rate.
2. The construction of 13 RDF plants as RDFP-3 model should be carried out gradually. It should begin with establishing one unit and, if successful, continue up to the 13th unit.
3. To construct 13 RDF plants utilising the RDFP-3 model, additional hot gas will be required for the extra box dryers, totalling 52 units. This is feasible because the cement plant operates ten kilns, thus providing sufficient additional hot gas.
4. An investigation is warranted to assess the potential for odour emissions and volatile toxic substances arising from the use of a box dryer in drying MSW, along with strategies for effective mitigation.
5. To ensure efficient logistical costs, the placement of RDF plant locations should be reasonably close between the source and the cement plant. It is also important to study the density of RDF to ensure it is compact enough to allow for maximum loading capacity in truck transportation.
6. To ensure that the business of RDF production remains sustainable, it is crucial to protect the treatment process. Should the domestic market obligation (DMO) coal price decrease,

it is necessary to maintain a minimum price for RDF and low-grade RDF. For instance, this could be set at 25% of the coal net heat price.

7. Establish robust monitoring and evaluation mechanisms to assess RDF projects' performance, environmental impact, and economic viability over time. Regular monitoring allows adjustments and improvements to be made, ensuring RDF initiatives' long-term sustainability and success.
8. To improve RDF quality, source-based waste segregation is vital, in which the materials are categorised into paper, plastic, metals, organics, glass, residues, and hazardous substances. This is stipulated by Indonesian Waste Management Law No. 18/2008 and Government Regulation No. 22/2021, which mandate source segregation and hazardous waste isolation. Effective enforcement and promotion of these laws are essential for enhancing RDF quality, reducing processing costs, and mitigating heavy metal pollution risks, notably mercury from hazardous wastes such as lamps and batteries.
9. The model of potential pollutant load, which consists of four scenarios, calculates and forecasts possible emissions into the air and from the product. This information is helpful for project planning. For further planning, it is necessary to have more accurate emission data. The modelling demonstrates how quickly one can reach the range of permissible emissions under worst-case scenarios involving RDF from MSW. Therefore, treating and controlling MSW is crucial to preventing these calculated extreme pollutant loads from occurring.

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Appendices

Appendix 1. Quantity of Particle Size Distribution Each City in Mg

City	Total Particle Size Distribution (mm)						
	>200	100-200	80-100	50-80	10-50	<10	Total (Mg)
Jakarta	10%	21%	17%	31%	11%	10%	11.6
Bogor	10%	21%	17%	32%	11%	10%	11.2
Depok	10%	21%	17%	31%	11%	10%	11.2
Bekasi	10%	21%	17%	32%	11%	10%	11.7
All Cities	10%	21%	17%	32%	11%	10%	45.7

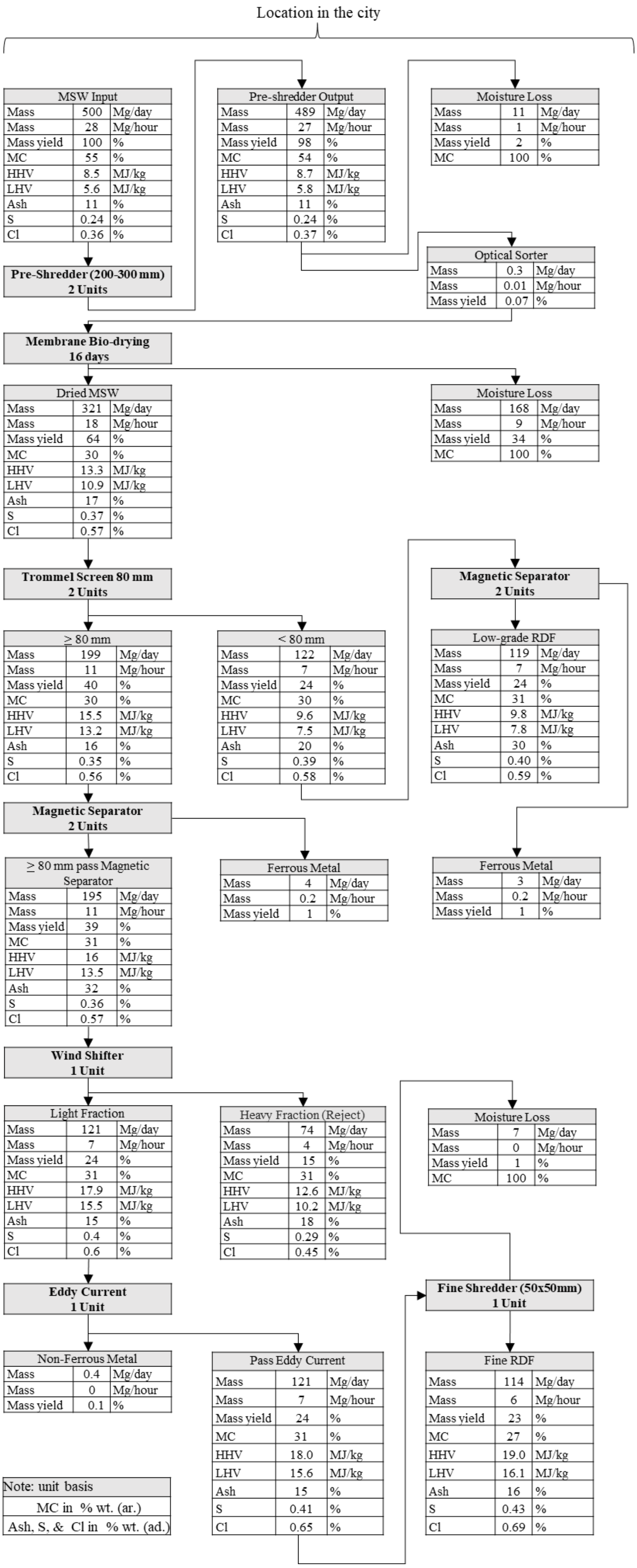
Appendix 2. Particle Size Distribution of MSW Fraction

MSW Fraction	Particle Size Distribution (mm)						
	>200	100-200	80-100	50-80	10-50	<10	Total
Combustible	93%	97%	96%	94%	62%	79%	88%
Organic (garden)	36%	11%	10%	4%	8%	2%	10%
Organic (leftover)	0%	31%	32%	47%	38%	63%	32%
Wood	34%	4%	3%	5%	0%	0%	5%
2D plastics	0%	37%	22%	25%	8%	8%	23%
3D plastics	0%	2%	3%	0%	0%	0%	1%
Paper	0%	8%	21%	10%	8%	6%	12%
Cardboard	0%	3%	2%	0%	0%	0%	1%
Textile	10%	2%	1%	2%	0%	0%	2%
Nappies	0%	0%	1%	0%	0%	0%	0%
Rubber	13%	0%	2%	1%	0%	0%	1%
Non-Combustible	7%	3%	4%	6%	38%	21%	12%
Metal (Fe)	6%	1%	1%	1%	2%	0%	1%
Metal (non-Fe)	0%	0%	0%	0%	0%	0%	0%
Glass	0%	2%	2%	2%	2%	0%	2%
Inert	0%	0%	0%	0%	5%	19%	2%
Stone	2%	0%	0%	0%	0%	0%	0%
Electronic waste	0%	0%	0%	0%	0%	0%	0%
Batteries	0%	0%	0%	1%	0%	0%	0%
Others	0%	0%	1%	1%	0%	0%	0%
Fines	0%	0%	0%	0%	29%	0%	4%
Hazardous waste	0%	0%	0%	0%	0%	2%	3%
Total (kg)	394	402	395	411	394	421	2,417

Appendix 3. MSW Fraction Each City

No	MSW Fraction	Jakarta	Bogor	Depok	Bekasi	Total
A	**Combustible**	**87%**	**87%**	**87%**	**88%**	**87%**
1	Organic (garden)	9%	10%	10%	10%	10%
2	Organic (leftover)	31%	33%	34%	33%	33%
3	Wood	6%	7%	4%	4%	5%
4	2D plastics	24%	20%	20%	25%	22%
5	3D plastics	2%	1%	1%	2%	2%
6	Paper	12%	10%	13%	11%	11%
7	Cardboard	1%	1%	1%	1%	1%
8	Textile	1%	3%	1%	2%	2%
9	Nappies	0%	0%	0%	0%	0%
10	Rubber	1%	1%	2%	1%	1%
B	**Non-combustible**	**13%**	**13%**	**13%**	**12%**	**13%**
1	Metal (Fe)	1%	1%	1%	1%	1%
2	Metal (non-Fe)	0%	0%	0%	0%	0%
3	Glass	2%	1%	2%	1%	2%
4	Inert	2%	2%	2%	2%	2%
5	Stone	0%	0%	0%	0%	0%
6	Electronic waste	0%	0%	0%	0%	0%
7	Batteries	0%	0%	0%	0%	0%
8	Others	4%	4%	4%	3%	4%
9	Fines	4%	4%	4%	3%	4%
10	Hazardous waste	0%	0%	0%	0%	0%
C	**Total (Mg)**	243	239	238	247	967

Appendix 4. RDFP-1 Mass Flow Model



Appendix 5. RDFP-2 Mass Flow Model

Location in the city

MSW Input		
Mass	500	Mg/day
Mass	28	Mg/hour
Mass yield	100	%
MC	55	%
HHV	8.5	MJ/kg
LHV	5.6	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.36	%

Pre-shredder Output		
Mass	489	Mg/day
Mass	27	Mg/hour
Mass yield	98	%
MC	54	%
HHV	8.7	MJ/kg
LHV	5.8	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.37	%

Moisture Loss		
Mass	11	Mg/day
Mass	1	Mg/hour
Mass yield	2	%
MC	100	%

Pre-Shredder (200-300 mm) 2 Units

Optical sorter		
Mass	0.3	Mg/day
Mass	0.01	Mg/hour
Mass yield	0.07	%

Bio-Drying with Turner & Transparent Roof 13 days

Moisture Loss		
Mass	168	Mg/day
Mass	9	Mg/hour
Mass yield	34	%
MC	100	%

Dried MSW		
Mass	321	Mg/day
Mass	18	Mg/hour
Mass yield	64	%
MC	30	%
HHV	13.3	MJ/kg
LHV	10.9	MJ/kg
Ash	17	%
S	0.37	%
Cl	0.57	%

Trommel Screen 80 mm 2 Units

Magnetic Separator 2 Units

> 80 mm		
Mass	199	v
Mass	11	Mg/hour
Mass yield	40	%
MC	30	%
HHV	15.5	MJ/kg
LHV	13.2	MJ/kg
Ash	16	%
S	0.35	%
Cl	0.56	%

< 80 mm		
Mass	122	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	30	%
HHV	9.6	MJ/kg
LHV	7.5	MJ/kg
Ash	20	%
S	0.39	%
Cl	0.58	%

Low-grade RDF		
Mass	119	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	31	%
HHV	9.8	MJ/kg
LHV	7.8	MJ/kg
Ash	30	%
S	0.40	%
Cl	0.59	%

Magnetic Separator 2 Units

≥ 80 mm pass Magnetic Separator		
Mass	195	Mg/day
Mass	11	Mg/hour
Mass yield	39	%
MC	31	%
HHV	15.9	MJ/kg
LHV	13.5	MJ/kg
Ash	16	%
S	0.36	%
Cl	0.57	%

Ferrous Metal		
Mass	4	Mg/day
Mass	0.2	Mg/hour
Mass yield	1	%

Ferrous Metal		
Mass	3	Mg/day
Mass	0.2	Mg/hour
Mass yield	1	%

Wind Shifter 1 Unit

Light Fraction		
Mass	121	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	31	%
HHV	17.9	MJ/kg
LHV	15.5	MJ/kg
Ash	15	%
S	0.41	%
Cl	0.65	%

Heavy Fraction (Reject)		
Mass	74	Mg/day
Mass	4	Mg/hour
Mass yield	15	%
MC	31	%
HHV	12.6	MJ/kg
LHV	10.2	MJ/kg
Ash	18	%
S	0.29	%
Cl	0.45	%

Moisture Loss		
Mass	7	Mg/day
Mass	0	Mg/hour
Mass yield	1	%
MC	100	%

Eddy Current 1 Unit

Fine Shredder (50x50mm) 1 Unit

Non-Ferrous Metal		
Mass	0.4	Mg/day
Mass	0	Mg/hour
Mass yield	0.1	%

Pass Eddy Current		
Mass	121	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	31	%
HHV	18.0	MJ/kg
LHV	15.6	MJ/kg
Ash	15	%
S	0.41	%
Cl	0.65	%

Fine RDF		
Mass	114	Mg/day
Mass	6	Mg/hour
Mass yield	23	%
MC	27	%
HHV	19.0	MJ/kg
LHV	16.1	MJ/kg
Ash	16	%
S	0.43	%
Cl	0.69	%

Note: unit basis
MC in % wt. (ar.)
Ash, S, & Cl in % wt. (ad.)

Appendix 6. RDFP-3 Mass Flow Model

Location in the city

MSW Input		
Mass	500	Mg/day
Mass	28	Mg/hour
Mass yield	100	%
MC	55	%
HHV	8.5	MJ/kg
LHV	5.6	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.36	%

Pre-Shredder (200-300 mm)
2 Units

Pre-shredder Output		
Mass	489	Mg/day
Mass	27	Mg/hour
Mass yield	98	%
MC	54	%
HHV	8.7	MJ/kg
LHV	5.8	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.37	%

Moisture Loss		
Mass	11	Mg/day
Mass	1	Mg/hour
Mass yield	2	%
MC	100	%

Trommel Screen 80 mm
4 Units

≥ 80 mm		
Mass	306	Mg/day
Mass	17	Mg/hour
Mass yield	61	%
MC	50	%
HHV	10.7	MJ/kg
LHV	7.9	MJ/kg
Ash	12	%
S	0.26	%
Cl	0.40	%

< 80mm		
Mass	183	Mg/day
Mass	10	Mg/hour
Mass yield	37	%
MC	61	%
HHV	5.4	MJ/kg
LHV	2.6	MJ/kg
Ash	11	%
S	0.22	%
Cl	0.32	%

Magnetic Separator
2 Units

Ferrous Metal		
Mass	3	Mg/day
Mass	0.2	Mg/hour
Mass yield	1 %	%

Low-grade RDF		
Mass	181	Mg/day
Mass	10	Mg/hour
Mass yield	36	%
MC	62	%
HHV	5.4	MJ/kg
LHV	2.6	MJ/kg
Ash	11	%
S	0.22	%
Cl	0.33	%

Deliver to the cement plant

Location in the cement plant

Box-drier
2 Units

Moisture Loss		
Mass	62	Mg/day
Mass	3	Mg/hour
Mass yield	12	%
MC	100	%

Dried Low-grade RDF		
Mass	119	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	42	%
HHV	8.3	MJ/kg
LHV	5.9	MJ/kg
Ash	17	%
S	0.34	%
Cl	0.50	%

Magnetic Separator
2 Units

≥80 mm pass Magnetic Separator		
Mass	301	Mg/day
Mass	17	Mg/hour
Mass yield	60	%
MC	51	%
HHV	10.9	MJ/kg
LHV	8.0	MJ/kg
Ash	12	%
S	0.26	%
Cl	0.41	%

Ferrous Metal		
Mass	4	Mg/day
Mass	0.2	Mg/hour
Mass yield	1 %	%

Wind Shifter
1 Unit

Light Fraction		
Mass	176	Mg/day
Mass	10	Mg/hour
Mass yield	35	%
MC	49	%
HHV	13.0	MJ/kg
LHV	10.2	MJ/kg
Ash	13	%
S	0.30	%
Cl	0.49	%

Heavy Fraction (Reject)		
Mass	125	Mg/day
Mass	7	Mg/hour
Mass yield	25	%
MC	53	%
HHV	7.9	MJ/kg
LHV	5.0	MJ/kg
Ash	9	%
S	0.20	%
Cl	0.30	%

Eddy Current
1 Unit

Non-Ferrous Metal		
Mass	0.4	Mg/day
Mass	0	Mg/hour
Mass yield	0.1	%

Pass Eddy Current		
Mass	176	Mg/day
Mass	10	Mg/hour
Mass yield	35	%
MC	49	%
HHV	13.0	MJ/kg
LHV	10.2	MJ/kg
Ash	14	%
S	0.31	%
Cl	0.49	%

Fine Shredder (50x50mm)
1 Unit

Moisture Loss		
Mass	13	Mg/day
Mass	1	Mg/hour
Mass yield	3	%
MC	100	%

Fine RDF		
Mass	163	Mg/day
Mass	9	Mg/hour
Mass yield	33	%
MC	45	%
HHV	14.1	MJ/kg
LHV	10.8	MJ/kg
Ash	15	%
S	0.33	%
Cl	0.53	%

Deliver to the cement plant

Box-drier
2 Units

Moisture Loss		
Mass	44	Mg/day
Mass	2	Mg/hour
Mass yield	9	%
MC	100	%

Dried Fine RDF		
Mass	119	Mg/day
Mass	7	Mg/hour
Mass yield	24	%
MC	25	%
HHV	19.2	MJ/kg
LHV	16.4	MJ/kg
Ash	20	%
S	0.45	%
Cl	0.72	%

Note: unit basis
MC in % wt. (ar.)
Ash, S, & Cl in % wt. (ad.)

Appendix 7 RDFP-4 Mass Flow Model

Location in the city

MSW Input		
Mass	500	Mg/day
Mass	28	Mg/hour
Mass yield	100	%
MC	55	%
HHV	8.5	MJ/kg
LHV	5.6	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.36	%

Pre-Shredder (200-300 mm)
2 Units

Pre-shredder Output		
Mass	489	Mg/day
Mass	28	Mg/hour
Mass yield	98	%
MC	54	%
HHV	8.7	MJ/kg
LHV	5.8	MJ/kg
Ash	11	%
S	0.24	%
Cl	0.37	%

Moisture Loss		
Mass	11	Mg/day
Mass	1	Mg/hour
Mass yield	2	%
MC	100	%

Optical sorter		
Mass	0.3	Mg/day
Mass	0.01	Mg/hour
Mass yield	0.07	%

Trommel Screen 80 mm
4 Units

> 80 mm		
Mass	306	Mg/day
Mass	17	Mg/hour
Mass yield	61	%
MC	50	%
HHV	10.7	MJ/kg
LHV	7.9	MJ/kg
Ash	12	%
S	0.26	%
Cl	0.40	%

< 80mm		
Mass	183	Mg/day
Mass	10	Mg/hour
Mass yield	37	%
MC	61	%
HHV	5.4	MJ/kg
LHV	2.6	MJ/kg
Ash	11	%
S	0.22	%
Cl	0.32	%

Bio-drying with turner & transparent roof 13 days

Moisture Loss		
Mass	68	Mg/day
Mass	4	Mg/hour
Mass yield	14	%
MC	100	%

Dried <80 mm		
Mass	116	Mg/day
Mass	6	Mg/hour
Mass yield	23	%
MC	38	
HHV	8.5	MJ/kg
LHV	6.2	MJ/kg
Ash	18	%
S	0.35	%
Cl	0.51	%

Magnetic Separator
2 Units

Ferrous Metal		
Mass	3	Mg/day
Mass	0.2	Mg/hour
Mass yield	1 %	%

Belt Drier
2 Units

Dried >80mm		
Mass	235	Mg/day
Mass	13	Mg/hour
Mass yield	47	%
MC	35	%
HHV	14.0	MJ/kg
LHV	11.5	MJ/kg
Ash	15	%
S	0.33	%
Cl	0.52	%

Moisture Loss		
Mass	70	Mg/day
Mass	4	Mg/hour
Mass yield	14	%
MC	100	%

Ferrous Metal		
Mass	4	Mg/day
Mass	0.2	Mg/hour
Mass yield	1 %	%

≥80 mm pass Magnetic Separator		
Mass	231	Mg/day
Mass	13	Mg/hour
Mass yield	46	%
MC	34	%
HHV	15.0	MJ/kg
LHV	12.6	MJ/kg
Ash	15	%
S	0.34	%
Cl	0.54	%

Low-grade RDF		
Mass	113	Mg/day
Mass	6	Mg/hour
Mass yield	23	%
MC	39	%
HHV	8.7	MJ/kg
LHV	6.4	MJ/kg
Ash	18	%
S	0.36	%
Cl	0.53	%

Magnetic Separator
2 Units

Wind Shifter
1 Unit

Light Fraction		
Mass	135	Mg/day
Mass	7	Mg/hour
Mass yield	27	%
MC	33	%
HHV	17	MJ/kg
LHV	14.6	MJ/kg
Ash	18	%
S	0.40	%
Cl	0.64	%

Heavy Fraction (Reject)		
Mass	96	Mg/day
Mass	5	Mg/hour
Mass yield	19	%
MC	39	%
HHV	10.3	MJ/kg
LHV	7.7	MJ/kg
Ash	12	%
S	0.25	%
Cl	0.39	%

Moisture Loss		
Mass	8	Mg/day
Mass	1	Mg/hour
Mass yield	2 %	%
MC	100	%

Eddy Current
1 Unit

Fine Shredder (50x50mm)
1 Unit

Non-Ferrous Metal		
Mass	0.4	Mg/day
Mass	0	Mg/hour
Mass yield	0.1	%

Pass Eddy Current		
Mass	135	Mg/day
Mass	7	Mg/hour
Mass yield	27	%
MC	34	%
HHV	17.1	MJ/kg
LHV	14.7	MJ/kg
Ash	18	%
S	0.40	%
Cl	0.64	%

Fine RDF		
Mass	127	Mg/day
Mass	7	Mg/hour
Mass yield	25	%
MC	30	%
HHV	18.2	MJ/kg
LHV	15.2	MJ/kg
Ash	19	%
S	0.42	%
Cl	0.68	%

Note: unit basis
MC in % wt. (ar.)
Ash, S, & Cl in % wt. (ad.)

Appendix 8. RDFP-1 Financial Model

Financial Calculation	Unit	Year		
		1	19	20
Revenue				
MSW input	Mg/year	182,500	182,500	182,500
RDF	Mg/year	41,683	41,683	41,683
Low Grade RDF	Mg/year	43,280	43,280	43,280
Metal	Mg/year	2,838	2,838	2,838
Reject	Mg/year	27,025	27,025	27,025
Tipping Fee	Euro	4,019,345.2	9,673,033.6	10,156,685.2
RDF Sales	Euro	1,002,712.7	1,002,712.7	1,002,712.7
RDF Carbon Credit	Euro	1,343,241.6	1,343,241.6	1,343,241.6
Low Grade RDF sales	Euro	500,379.0	500,379.0	500,379.0
Low Grade RDF carbon credit	Euro	363,891.6	363,891.6	363,891.6
Metal Sales	Euro	591,181.6	1,422,749.1	1,493,886.6
Total Revenue	Euro	7,820,751.8	14,306,007.6	14,860,796.7
		-	-	-
Variable Cost		-	-	-
RDF Transportation to The Cement Plant	Euro	310,138.9	885,241.6	938,356.0
Low Grade RDF Transportation to the Cement Plant	Euro	257,616.1	735,323.7	779,443.1
Reject Transportation	Euro	270,252.5	771,392.4	817,675.9
Maintenance: Building-Civil Works	Euro	194,503.8	555,179.7	588,490.5
Maintenance: Equipment	Euro	1,015,140.4	2,897,554.9	3,071,408.2
Electricity	Euro	517,422.7	1,476,899.9	1,565,513.9
Fuel	Euro	718,007.1	2,049,435.9	2,172,402.1
Total Variable Cost	Euro	3,283,081.5	9,371,028.0	9,933,289.7
Fix Cost	Euro	-	-	-
Labour	Euro	639,166.7	912,887.4	931,145.1
Depreciation	Euro	-	-	-
Equipment Depreciation	Euro	-	-	-
Hopper, Dosing & Feeder	Euro	15,381.0	15,381.0	15,381.0
Truck Scale	Euro	9,228.6	9,228.6	9,228.6
Optical Sorter	Euro	23,809.5	23,809.5	23,809.5
Pre-shredder	Euro	119,510.0	119,510.0	119,510.0
Membrane Biodying	Euro	250,000.0	250,000.0	250,000.0
Turning Machine	Euro	-	-	-
Trommel	Euro	109,589.3	109,589.3	109,589.3
Magnetic Separator	Euro	40,375.0	40,375.0	40,375.0
Windshifter	Euro	31,492.5	31,492.5	31,492.5
Eddy Current	Euro	28,839.3	28,839.3	28,839.3
High Speed Fine Shredder	Euro	103,821.4	103,821.4	103,821.4
Belt Drier	Euro	-	-	-
Conveyor System	Euro	66,419.8	66,419.8	66,419.8
Loader	Euro	64,888.4	64,888.4	64,888.4
Dump Truck	Euro	19,466.5	19,466.5	19,466.5
Crane	Euro	11,896.2	11,896.2	11,896.2
Power Transmission	Euro	14,227.4	14,227.4	14,227.4
Electric & Control System include Biodying	Euro	11,012.9	11,012.9	11,012.9
Electric & Control System without Drying	Euro	-	-	-
Electric & Control System include belt drier	Euro	-	-	-
Equipment substructure	Euro	18,264.9	18,264.9	18,264.9
Pipe & Blower System	Euro	11,564.6	11,564.6	11,564.6
Laboratorium	Euro	9,613.1	9,613.1	9,613.1
Instrument	Euro	9,613.1	9,613.1	9,613.1
Safety & Monitoring	Euro	11,535.7	11,535.7	11,535.7
Total Equipment Depreciation	Euro	980,549.2	980,549.2	980,549.2
Building-Civil Works Depreciation	Euro	-	-	-
Treatment Area	Euro	59,523.8	59,523.8	59,523.8
RDF Storage	Euro	41,666.7	41,666.7	41,666.7
Security	Euro	500.0	500.0	500.0
Gate	Euro	1,333.3	1,333.3	1,333.3
Office & Lab	Euro	11,904.8	11,904.8	11,904.8
Workshop	Euro	11,904.8	11,904.8	11,904.8
Safety & Fire	Euro	7,142.9	7,142.9	7,142.9
Housing	Euro	2,381.0	2,381.0	2,381.0
Central Control Room	Euro	3,571.4	3,571.4	3,571.4
Utility	Euro	11,904.8	11,904.8	11,904.8
Electrical	Euro	16,666.7	16,666.7	16,666.7
Truck Scale area	Euro	8,333.3	8,333.3	8,333.3
Washing Area	Euro	5,714.3	5,714.3	5,714.3
Road, Drainage, & Landscape	Euro	14,137.5	14,137.5	14,137.5
Biodrying Area RDFP-1 (34 Lanes,4.5mx65m), without roof	Euro	277,714.3	277,714.3	277,714.3
Biodrying Area RDFP-2 (28 Lanes,4.5mx65m) with transparent roof	Euro	-	-	-
Biodrying Area RDFP-3&4 (28 Lanes,4.5mx28m) with transparent roof	Euro	-	-	-
Land Preparation	Euro	11,860.0	11,860.0	11,860.0
Total Building-Civil Works Depreciation	Euro	486,259.4	486,259.4	486,259.4
Insurance	Euro	39,221.3	39,221.3	39,221.3
Total Fix Cost	Euro	2,145,196.5	2,418,917.2	2,437,175.0
Total Cost	Euro	5,428,278.0	11,789,945.2	12,370,464.7
Gain (lost)	Euro	2,392,473.8	2,516,062.3	2,490,332.1
Debt Bearing	Euro	(2,181,400.3)	-	-
Income Before Tax	Euro	211,073.5	2,516,062.3	2,490,332.1
Tax Income	Euro	46,436.2	553,533.7	547,873.1
Net Income	Euro	164,637.3	1,962,528.6	1,942,459.0
Opex	Euro	3,922,248.2	10,283,915.4	10,864,434.9
Net Income - Equity	Euro	(9,856,991.7)	379,899.5	2,322,358.5
BEP		not yet	BEP	BEP
Payback Period	**Years**	**-**	18.8	

Appendix 9. RDFP-2 Financial Model

Financial Calculation	Unit	Year		
		1	16	20
Revenue				
MSW input	Mg/year	182,500	182,500	182,500
RDF	Mg/year	41,683	41,683	41,683
Low Grade RDF	Mg/year	43,280	43,280	43,280
Metal	Mg/year	2,838	2,838	2,838
Reject	Mg/year	27,025	27,025	27,025
Tipping Fee	Euro	4,019,345.2	8,355,930.1	10,156,685.2
RDF Sales	Euro	1,002,712.7	1,002,712.7	1,002,712.7
RDF Carbon Credit	Euro	1,343,241.6	1,343,241.6	1,343,241.6
Low Grade RDF sales	Euro	500,379.0	500,379.0	500,379.0
Low Grade RDF carbon credit	Euro	363,891.6	363,891.6	363,891.6
Metal Sales	Euro	591,181.6	1,229,024.2	1,493,886.6
Total Revenue	Euro	7,820,751.8	12,795,179.2	14,860,796.7
	Euro	-	-	-
Variable Cost	Euro	-	-	-
RDF Transportation to The Cement Plant	Euro	310,138.9	743,265.9	938,356.0
Low Grade RDF Transportation to the Cement Plant	Euro	257,616.1	617,392.0	779,443.1
Reject Transportation	Euro	270,252.5	647,675.9	817,675.9
Maintenance: Building-Civil Works	Euro	213,480.9	511,619.4	645,907.7
Maintenance: Equipment	Euro	941,561.8	2,256,507.6	2,848,788.9
Electricity	Euro	517,422.7	1,240,033.6	1,565,513.9
Fuel	Euro	732,085.7	1,754,486.0	2,214,998.2
Total Variable Cost	Euro	3,242,558.6	7,770,980.5	9,810,683.8
Fix Cost	Euro	-	-	-
Labour	Euro	639,166.7	1,151,103.1	1,346,627.8
Depreciation	Euro	-	-	-
Equipment Depreciation	Euro	-	-	-
Hopper, Dosing & Feeder	Euro	15,381.0	15,381.0	15,381.0
Truck Scale	Euro	9,228.6	9,228.6	9,228.6
0	Euro	23,809.5	23,809.5	23,809.5
Pre-shredder	Euro	119,510.0	119,510.0	119,510.0
Membrane Biodying	Euro	-	-	-
Turning Machine	Euro	214,285.7	214,285.7	214,285.7
Trommel	Euro	109,589.3	109,589.3	109,589.3
Magnetic Separator	Euro	40,375.0	40,375.0	40,375.0
Windshifter	Euro	31,492.5	31,492.5	31,492.5
Eddy Current	Euro	28,839.3	28,839.3	28,839.3
High Speed Fine Shredder	Euro	103,821.4	103,821.4	103,821.4
Belt Drier	Euro	-	-	-
Conveyor System	Euro	66,419.8	66,419.8	66,419.8
Loader	Euro	21,629.5	21,629.5	21,629.5
Dump Truck	Euro	19,466.5	19,466.5	19,466.5
Crane	Euro	11,896.2	11,896.2	11,896.2
Power Transmission	Euro	14,227.4	14,227.4	14,227.4
Electric & Control System include Biodying	Euro	11,012.9	11,012.9	11,012.9
Electric & Control System without Drying	Euro	-	-	-
Electric & Control System include belt drier	Euro	-	-	-
Equipment substructure	Euro	18,264.9	18,264.9	18,264.9
Pipe & Blower System	Euro	11,564.6	11,564.6	11,564.6
Laboratorium	Euro	9,613.1	9,613.1	9,613.1
Instrument	Euro	9,613.1	9,613.1	9,613.1
Safety & Monitoring	Euro	11,535.7	11,535.7	11,535.7
Total Equipment Depreciation	Euro	901,576.0	901,576.0	901,576.0
Building-Civil Works	Euro	-	-	-
Treatment Area	Euro	59,523.8	59,523.8	59,523.8
RDF Storage	Euro	41,666.7	41,666.7	41,666.7
Security	Euro	500.0	500.0	500.0
Gate	Euro	1,333.3	1,333.3	1,333.3
Office & Lab	Euro	11,904.8	11,904.8	11,904.8
Workshop	Euro	11,904.8	11,904.8	11,904.8
Safety & Fire	Euro	7,142.9	7,142.9	7,142.9
Housing	Euro	2,381.0	2,381.0	2,381.0
Central Control Room	Euro	3,571.4	3,571.4	3,571.4
Utility	Euro	11,904.8	11,904.8	11,904.8
Electrical	Euro	16,666.7	16,666.7	16,666.7
Truck Scale area	Euro	8,333.3	8,333.3	8,333.3
Washing Area	Euro	5,714.3	5,714.3	5,714.3
Road, Drainage, & Landscape	Euro	14,137.5	14,137.5	14,137.5
Biodrying Area RDFP-1 (34 Lanes,4.5mx65m), without roof	Euro	-	-	-
Biodrying Area RDFP-2 (28 Lanes,4.5mx65m) with transparent roof	Euro	324,000.0	324,000.0	324,000.0
Biodrying Area RDFP-3&4 (28 Lanes,4.5mx28m) with transparent roof	Euro	-	-	-
Land Preparation	Euro	13,017.1	13,017.1	13,017.1
Total Building-Civil Works Depreciation	Euro	533,702.2	533,702.2	533,702.2
Insurance	Euro	39,639.9	39,639.9	39,639.9
Total Fix Cost	Euro	2,114,084.8	2,626,021.2	2,821,545.9
Total Cost	Euro	5,356,643.4	10,397,001.6	12,632,229.7
Gain (lost)	Euro	2,464,108.4	2,398,177.5	2,228,567.0
Debt Bearing	Euro	(2,204,589.9)	-	-
Income Before Tax	Euro	259,518.5	2,398,177.5	2,228,567.0
Tax Income	Euro	57,094.1	527,599.1	490,284.7
Net Income	Euro	202,424.4	1,870,578.5	1,738,282.3
Opex	Euro	3,881,725.3	8,922,083.5	11,157,311.5
Net Income - Investment	Euro	(9,925,740.4)	175,910.8	570,854.7
BEP		not yet	BEP	BEP
Payback Period	**Year**	**-**	**15.9**	

Appendix 10. RDFP-3 Financial Model

Financial Calculation	Unit	Year		
		1	6	20
Revenue				
MSW input	Mg/year	182,500	182,500	182,500
RDF	Mg/year	41,683	41,683	41,683
Low Grade RDF	Mg/year	43,280	43,280	43,280
Metal	Mg/year	2,838	2,838	2,838
Reject	Mg/year	45,559	45,559	45,559
Tipping Fee	Euro	4,019,345.2	5,129,816.2	10,156,685.2
RDF Sales	Euro	1,019,126.3	1,019,126.3	1,019,126.3
RDF Carbon Credit	Euro	1,258,330.9	1,258,330.9	1,258,330.9
Low Grade RDF sales	Euro	383,114.1	383,114.1	383,114.1
Low Grade RDF carbon credit	Euro	261,516.3	261,516.3	261,516.3
Metal Sales	Euro	591,181.6	754,514.2	1,493,886.6
Total Revenue	Euro	7,532,614.5	8,806,418.0	14,572,659.4
Variable Cost	Euro	-	-	-
RDF Transportation to The Cement Plant	Euro	310,138.9	415,035.8	938,356.0
Low Grade RDF Transportation to the Cement Plant	Euro	257,616.1	344,748.5	779,443.1
Reject Transportation	Euro	455,586.9	609,678.0	1,378,423.4
Maintenance: Building-Civil Works	Euro	92,783.8	124,165.6	280,726.5
Maintenance: Equipment	Euro	964,441.3	1,290,640.0	2,918,013.1
Electricity	Euro	517,422.7	692,428.3	1,565,513.9
Fuel	Euro	380,121.4	508,688.2	1,150,095.2
Total Variable Cost	Euro	2,978,111.0	3,985,384.3	9,010,571.2
Fix Cost	Euro	-	-	-
Labour	Euro	639,166.7	777,644.0	1,346,627.8
Depreciation	Euro	-	-	-
Equipment Depreciation	Euro	-	-	-
Hopper, Dosing & Feeder	Euro	15,381.0	15,381.0	15,381.0
Truck Scale	Euro	9,228.6	9,228.6	9,228.6
0	Euro	23,809.5	23,809.5	23,809.5
Pre-shredder	Euro	119,510.0	119,510.0	119,510.0
Membrane Biodying	Euro	-	-	-
Turning Machine	Euro	-	-	-
Trommel	Euro	219,178.6	219,178.6	219,178.6
Magnetic Separator	Euro	40,375.0	40,375.0	40,375.0
Windshifter	Euro	31,492.5	31,492.5	31,492.5
Eddy Current	Euro	28,839.3	28,839.3	28,839.3
High Speed Fine Shredder	Euro	103,821.4	103,821.4	103,821.4
Box Drying	Euro	100,000.0	100,000.0	100,000.0
Belt Drier	Euro	-	-	-
Conveyor System	Euro	66,419.8	66,419.8	66,419.8
Loader	Euro	21,629.5	21,629.5	21,629.5
Dump Truck	Euro	19,466.5	19,466.5	19,466.5
Crane	Euro	11,896.2	11,896.2	11,896.2
Power Transmission	Euro	14,227.4	14,227.4	14,227.4
Electric & Control System include Biodying	Euro	-	-	-
Electric & Control System without Drying	Euro	6,607.8	6,607.8	6,607.8
Electric & Control System include belt drier	Euro	-	-	-
Equipment substructure	Euro	18,264.9	18,264.9	18,264.9
Pipe & Blower System	Euro	5,782.3	5,782.3	5,782.3
Laboratorium	Euro	9,613.1	9,613.1	9,613.1
Instrument	Euro	9,613.1	9,613.1	9,613.1
Safety & Monitoring	Euro	11,535.7	11,535.7	11,535.7
Total Equipment Depreciation	Euro	886,692.0	886,692.0	886,692.0
Building-Civil Works	Euro	-	-	-
Treatment Area	Euro	59,523.8	59,523.8	59,523.8
RDF Storage	Euro	41,666.7	41,666.7	41,666.7
Security	Euro	500.0	500.0	500.0
Gate	Euro	1,333.3	1,333.3	1,333.3
Office & Lab	Euro	11,904.8	11,904.8	11,904.8
Workshop	Euro	11,904.8	11,904.8	11,904.8
Safety & Fire	Euro	7,142.9	7,142.9	7,142.9
Housing	Euro	2,381.0	2,381.0	2,381.0
Central Control Room	Euro	3,571.4	3,571.4	3,571.4
Utility	Euro	11,904.8	11,904.8	11,904.8
Electrical	Euro	16,666.7	16,666.7	16,666.7
Truck Scale area	Euro	8,333.3	8,333.3	8,333.3
Washing Area	Euro	5,714.3	5,714.3	5,714.3
Road, Drainage, & Landscape	Euro	14,137.5	14,137.5	14,137.5
Biodrying Area RDFP-1 (34 Lanes,4.5mx65m), without roof	Euro	-	-	-
Biodrying Area RDFP-2 (28 Lanes,4.5mx65m) with transparent roof	Euro	-	-	-
Biodrying Area RDFP-3&4 (28 Lanes,4.5mx28m) with transparent roof	Euro	-	-	-
Land Preparation	Euro	4,917.1	4,917.1	4,917.1
Total Building-Civil Works Depreciation	Euro	201,602.2	201,602.2	201,602.2
Insurance	Euro	28,231.0	28,231.0	28,231.0
Total Fix Cost	Euro	1,755,692.0	1,894,169.3	2,463,153.1
Total Cost	Euro	4,733,803.0	5,879,553.6	11,473,724.3
Gain (lost)	Euro	2,798,811.5	2,926,864.4	3,098,935.1
Debt Bearing	Euro	(1,572,689.3)	-	-
Income Before Tax	Euro	1,226,122.2	2,926,864.4	3,098,935.1
Tax Income	Euro	269,746.9	643,910.2	681,765.7
Net Income	Euro	956,375.3	2,282,954.2	2,417,169.4
Opex	Euro	3,617,277.7	4,763,028.3	10,357,199.0
Net Income - Investment	Euro	(6,268,758.4)	42,500.1	17,955,790.8
BEP		not yet	BEP	BEP
Payback Period	**Year**	**-**	**6.0**	

Appendix 11. RDFP-4 Financial Model

Financial Calculation	Unit	Year		
		1	19	20
Revenue				
MSW input	Mg/year	182,500	182,500	182,500
RDF	Mg/year	41,683	41,683	41,683
Low Grade RDF	Mg/year	43,280	43,280	43,280
Metal	Mg/year	2,838	2,838	2,838
Reject	Mg/year	35,128	35,128	35,128
Tipping Fee	Euro	4,019,345.2	9,673,033.6	10,156,685.2
RDF Sales	Euro	1,019,126.3	1,019,126.3	1,019,126.3
RDF Carbon Credit	Euro	1,256,686.1	1,256,686.1	1,256,686.1
Low Grade RDF sales	Euro	414,670.8	414,670.8	414,670.8
Low Grade RDF carbon credit	Euro	511,331.1	511,331.1	511,331.1
Metal Sales	Euro	591,181.6	1,422,749.1	1,493,886.6
Total Revenue	Euro	7,812,341.1	14,297,596.9	14,852,386.0
	Euro	-	-	-
Variable Cost	Euro	-	-	-
RDF Transportation to The Cement Plant	Euro	310,138.9	885,241.6	938,356.0
Low Grade RDF Transportation to the Cement Plant	Euro	257,616.1	735,323.7	779,443.1
Reject Transportation	Euro	351,284.7	1,002,685.8	1,062,846.9
Maintenance: Building-Civil Works	Euro	138,758.4	396,063.5	419,827.3
Maintenance: Equipment	Euro	1,026,759.1	2,930,718.7	3,106,561.8
Electricity	Euro	839,374.6	2,395,859.8	2,539,611.4
Fuel	Euro	497,442.9	1,419,870.6	1,505,062.9
Total Variable Cost	Euro	3,421,374.7	9,765,763.7	10,351,709.5
Fix Cost	Euro	-	-	-
Labour	Euro	639,166.7	1,294,834.4	1,346,627.8
Depreciation	Euro	-	-	-
Equipment Depreciation	Euro	-	-	-
Hopper, Dosing & Feeder	Euro	15,381.0	15,381.0	15,381.0
Truck Scale	Euro	9,228.6	9,228.6	9,228.6
Optical Sorter	Euro	23,809.5	23,809.5	23,809.5
Pre-shredder	Euro	119,510.0	119,510.0	119,510.0
Membrane Biodying	Euro	-	-	-
Turning Machine	Euro	71,428.6	71,428.6	71,428.6
Trommel	Euro	219,178.6	219,178.6	219,178.6
Magnetic Separator	Euro	40,375.0	40,375.0	40,375.0
Windshifter	Euro	31,492.5	31,492.5	31,492.5
Eddy Current	Euro	28,839.3	28,839.3	28,839.3
High Speed Fine Shredder	Euro	103,821.4	103,821.4	103,821.4
Belt Drier	Euro	90,452.4	90,452.4	90,452.4
Conveyor System	Euro	66,419.8	66,419.8	66,419.8
Loader	Euro	21,629.5	21,629.5	21,629.5
Dump Truck	Euro	19,466.5	19,466.5	19,466.5
Crane	Euro	11,896.2	11,896.2	11,896.2
Power Transmission	Euro	14,227.4	14,227.4	14,227.4
Electric & Control System include Biodying	Euro	-	-	-
Electric & Control System without Drying	Euro	-	-	-
Electric & Control System include belt drier	Euro	16,422.8	16,422.8	16,422.8
Equipment substructure	Euro	18,264.9	18,264.9	18,264.9
Pipe & Blower System	Euro	5,782.3	5,782.3	5,782.3
Laboratorium	Euro	9,613.1	9,613.1	9,613.1
Instrument	Euro	9,613.1	9,613.1	9,613.1
Safety & Monitoring	Euro	11,535.7	11,535.7	11,535.7
Total Equipment Depreciation	Euro	958,388.0	958,388.0	958,388.0
Building-Civil Works	Euro	-	-	-
Treatment Area	Euro	59,523.8	59,523.8	59,523.8
RDF Storage	Euro	41,666.7	41,666.7	41,666.7
Security	Euro	500.0	500.0	500.0
Gate	Euro	1,333.3	1,333.3	1,333.3
Office & Lab	Euro	11,904.8	11,904.8	11,904.8
Workshop	Euro	11,904.8	11,904.8	11,904.8
Safety & Fire	Euro	7,142.9	7,142.9	7,142.9
Housing	Euro	2,381.0	2,381.0	2,381.0
Central Control Room	Euro	3,571.4	3,571.4	3,571.4
Utility	Euro	11,904.8	11,904.8	11,904.8
Electrical	Euro	16,666.7	16,666.7	16,666.7
Truck Scale area	Euro	8,333.3	8,333.3	8,333.3
Washing Area	Euro	5,714.3	5,714.3	5,714.3
Road, Drainage, & Landscape	Euro	14,137.5	14,137.5	14,137.5
Biodrying Area RDFP-1 (34 Lanes,4.5mx65m), without roof	Euro	-	-	-
Biodrying Area RDFP-2 (28 Lanes,4.5mx65m) with transparent roof	Euro	-	-	-
Biodrying Area RDFP-3&4 (28 Lanes,4.5mx28m) with transparent roof	Euro	141,750.0	141,750.0	141,750.0
Land Preparation	Euro	8,460.9	8,460.9	8,460.9
Total Building-Civil Works Depreciation	Euro	346,896.0	346,896.0	346,896.0
Insurance	Euro	33,972.6	33,972.6	33,972.6
Total Fix Cost	Euro	1,978,423.3	2,634,091.0	2,685,884.4
Total Cost	Euro	5,399,797.9	12,399,854.7	13,037,593.9
Gain (lost)	Euro	2,412,543.2	1,897,742.3	1,814,792.2
Debt Bearing	Euro	(1,890,694.3)	-	-
Income Before Tax	Euro	521,848.9	1,897,742.3	1,814,792.2
Tax Income	Euro	114,806.8	417,503.3	399,254.3
Net Income	Euro	407,042.1	1,480,239.0	1,415,537.9
Opex	Euro	4,060,541.3	11,060,598.0	11,698,337.2
Net Income - Investment	Euro	(8,279,046.6)	(181,668.7)	1,233,869.2
BEP		not yet	not yet	BEP
Payback Period	**Year**			19.7