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Fuel blending Options in cement pyro processing of Messebo Cement factory by Co firing of Sawdust and Coal

By
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In
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Under Supervisor of

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This is to confirm the thesis provided by Guesh Tewele, entitled “Fuel Blending Options in Cement Pyro Processing of Messebo Cement Factory by Cofiring of Sawdust and Coal.” is submitted in partial fulfillment of the degree of Master of Science in Sustainable Energy Technology under mechanical and industrial engineering that complies with the regulations of the university and meets the accepted standards concerning originality and quality.

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Declaration

I, the undersigned, declare that this thesis entitled "Fuel blending Options in Cement Pyro Processing of Messebo Cement Factory by Cofiring of Sawdust and Coal" is my original work and has not previously been submitted by any other person for the award of a degree at this or any other university, and that all resources and material used for this thesis have been properly acknowledged.

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This thesis is submitted for examination with my approval as the university advisor

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Abstract

This research assesses the technical, economic, and environmental viability of co-firing biomass fuels (eucalyptus sawdust, olea sawdust, and pine sawdust) alongside coal in cement manufacturing at Messebo Cement Factory. The evaluation emphasizes fuel blend composition, calorific values, combustion properties, and the potential for emissions reduction. Employing a mass-based fuel blend composition model, the study determines the molar composition of the blended fuels while examining their performance across 10%, 15%, and 20% co-firing ratios.

Key results indicate that co-firing biomass significantly lowers CO_2 emissions compared to coal. At a co-firing rate of 10%, eucalyptus sawdust emits 0. 46426 kg of CO_2 per kg of cement, in contrast to 0. 760 kg for coal by itself. This results in a CO_2 emissions reduction of 0. 304875%, which escalates to 1. 009417% at a co-firing rate of 20% for olea and pine sawdust. The flame temperature of 1770 K (1497°C) for 10% eucalyptus co-firing satisfies kiln operational specifications, confirming its technical feasibility.

From an economic standpoint, substituting 10% of coal with eucalyptus yields approximately 75,297,000 birr in annual savings, with savings rising to 150,600,000 birr at a 20% co-firing rate. The cost of eucalyptus (0. 38205 birr/kg of cement) is considerably lower than that of coal (1. 637 birr/kg of cement), leading to a 7. 67% decrease in fuel expenses at a 10% co-firing rate. Moreover, 10% eucalyptus co-firing decreases coal consumption by 5. 6%, which further boosts economic and environmental advantages.

Environmental benefits encompass significant reductions in SO_2 and NO_x emissions. For instance, 20% eucalyptus co-firing decreases SO_2 emissions by 19. 15264 units and NO_x emissions by 12. 49865 units. Pine sawdust exhibits the greatest reduction in SO_2 (19. 77646 units at 20% co-firing), while olea sawdust achieves the most substantial reduction in NO_x (13. 02422 units at 20% co-firing). A lower ash content (18. 67% at 20% co-firing) and minimal sulfur content in biomass further enhance combustion efficiency and lessen environmental impacts.

The study also underscores the practical use of pine sawdust as an alternative fuel, which lowers the air-to-fuel ratio, excess air ratio, oxygen demands, flame temperature, as well as SO_2 and NO_x emissions. Locally sourced pine sawdust offers benefits such as decreased transportation expenses, reduced moisture content, and less biological degradation. It can be processed and burned in a manner similar to coal or pet coke, needing only slight modifications.

The thesis concludes that co-firing biomass fuels, especially pine sawdust, represents a feasible and sustainable approach to cement production, delivering considerable environmental and economic advantages. It suggests additional actions like waste heat recovery, alternative raw material usage, carbon capture, and the integration of renewable energy to further enhance system efficiency. Co-firing coal with biomass provides significant benefits for cement kiln pyro processing but necessitates precise optimization and execution suited to specific operational circumstances.

Keywords: Co-firing

Coal, Sawdust, Biomass, Cement kiln, Pyro-processing, Emission reduction. Feasibility analysis, Fuel properties, Combustion characteristics

1. INTRODUCTION

Energy scarcity is one of the main problems of the modern world. To complete their daily tasks, people have become more dependent on fossil fuel supplies, which lead to energy waste during the conversion of primary energy and significant global challenges. Therefore, making effective use of energy is crucial to solving the growing issues associated with the global energy and environmental crisis.

Over the past few decades, there has been a significant increase in the global demand for energy due to rapid industrialization and global improvements in living standards. Furthermore, excessive fossil fuel consumption severely increases the need for energy.

As a result, it has heightened the need to look for renewable, eco-friendly, sustainable, affordable, and efficient alternative energy sources to help address today's environmental issues

Determining wasteful energy use and taking action to reduce or identify it is necessary for improving energy efficiency.

The level of production itself shouldn't be affected; only the amount of energy consumed and the expenses related to generating that production should. This implies reduced energy costs and hence increased profitability. This is the most important stage in achieving the three goals of energy policy: supply security, environmental preservation, financial growth, and energy cost reduction. Almost one-third of the world's energy consumption and greenhouse gas emissions are attributable to manufacturing, mainly to the major primary materials sectors of aluminum, cement, paper, petrochemicals, iron and steel, and chemicals. Understanding how this energy is used, as well as national and international trends, and the possibilities for enhancing efficiency is vital.

Ethiopia's more energy-intensive industrial sectors, like the cement, sugar, and textile industries, are severely affected by high energy costs and consumption. Socioeconomic development is significantly influenced by the construction industry. The industry is a separate economic sector that directly supports economic expansion. It offers the framework on which other industries can expand by building the actual facilities needed for production.

The cement industry is one of these plants that mainly uses electricity and fuel. To provide their customers with enough electricity, both the government and private citizens are putting a lot of effort into this endeavor. To guarantee that the energy generated today is used efficiently or to increase awareness of energy conservation, especially among the industrial sectors, not much is being done.

Even though this strategy hasn't been implemented yet, the Ethiopian Electric and Power Corporation (EEPCO) has been able to monitor these locations more effectively, allowing industries to maintain higher levels of efficiency in their electricity consumption. However, as a result, they incur large losses in energy bills, which among other things negatively impacts the environment and makes certain industries less competitive. The cement industry is one of the primary energy-intensive sectors that make a substantial economic contribution to a country.

There are four integrated cement factories in Ethiopia's cement sector. One of these is in the north of the nation, and the other three are in the center of Oromia. These have been installed with a total capacity of about 1,366,000 million tons of ordinary Portland cement annually in Ethiopia (Yosef dejene, 2004) .

Table 1 presents the installed capacities and locations of the cement plants in Ethiopia.

The cement industry is energy-based which constitutes 45 % of the cost of production. The total average annual consumption of furnace oil by these factories based on their installed clinker capacity and average oil consumption is estimated to reach 120 million liters or around 30 million dollars in value (Yosef Dejene, 2004).

Regional state	Name of cement plant	Operating unit	Year Established in E.C	Installed Cement capacity tone/year
Tigrai	Messebo	Line 1	1992	900,000
		Line 2	2002	900000
Oromia	Muger	Line 1	1977	350000
		Line 2	1982	350000
Driedawa	Driedawa	Line 1	1936	36000
Addis Ababa	Addis Ababa	Line 1	1964	70000

Table 1 Ethiopian cement plants installed capacity

The Ethiopian Commercial Code established the EFFORT (Endowment Fund for the Rehabilitation of Tigray) group of firms, which includes Messebo Cement Factory Private Limited Company (MCF PLC). The corporation has ETB 240 million in paid-up capital. The company is situated 780 kilometers from Ethiopia's capital, Addis Ababa, in Mekelle Town, in the Regional State of Tigray. The factory sits 15 kilometers northwest of Mekelle Town, close to the Messebo Hills. A Turkish business called ENKA built and installed the factory's first cement line. World-famous Danish cement technology supplier FLSmidth designed and provided the plant's machinery.

The first line's investment capital is approximately ETB 1.2 billion, while the second line's is approximately ETB 2 billion. Portland Pozzolana Cement (PPC), Portland Limestone Cement (PLC), Ordinary Portland Cement (OPC), and Low Heat of Hydration Cement (LHHS) are all produced by the firm. The plant currently produces protean cement types up to C-45 concrete grades, which are used in both light and heavy construction. With 300 operating days a year, the plant can produce 7,000 tons of cement per day and 2,100,000 tons of cement annually (messebo, messebo, 2015).

The company uses silica sand, iron ore, gypsum, limestone, shale, and other additives as raw materials. The various raw materials that are necessary for the operation of the plant are taken out of various locations. These are all provided by the company on an almost exclusive basis.

This factory's paper sack mill was started in 2002 E.C. to manufacture and provide paper sacks for the packaging of various items, including fillers, cement, and lime.

The factory has an annual production capacity of 60 million pieces at 50 kg.

The factory produces the following cement products, which are checked continuously:

Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and Portland limestone cement (PLC).
Therefore OPC is a type of cement with a proportion of 95% clinker and 5% gypsum; whereas PPC is a type of cement with a proportion of 70% clinker and 25% pozzolana and 5% gypsum. But in the case of PLC, it is a type of cement with a proportion of 80% clinker and 15 to 20 high-grade limestones. The type of kiln technology used by the Messebo cement factory is a dry process five-stage preheater kiln with a rotary cooler (messebo, messebo, 2015).

Fuel and electricity are the two main energy inputs used by the Messebo Cement Factory to carry out its operations. An essential component in the manufacturing of Messebo cement is coal and oil primarily employed in a kiln to produce heat, or thermal energy, which is needed to produce clinker.

This industry uses coal that has been domestically cleaned to lower the amount of ash in the coal that is shipped from Jimma mines. It also, to the greatest extent feasible, blends lignite with coal. Pet coke is a residual product from oil refineries with a high calorific value and negligible ash level, but it frequently has a higher sulfur content than coal. Pet coke has been shown to be an excellent alternative fuel to coal. Imports of South African coal with higher heat and lower ash content were essentially forbidden and subject to heavy charges.

Because of the inconsistent quality of coal, limited supply, and transportation congestion, it is now necessary to import coal from places like South Africa, Kenya, etc.Even though it has made it easier for the cement industry to obtain high-quality coal, the import of coal remains expensive and a burden on the national exchequer.

Improving clinker quality, productivity, and energy efficiency is becoming more difficult because of the unstable and declining quality of coal. The usage of these coals leads to several operational issues, including incorrect and inefficient burning, increased coal consumption per unit, and reduced operational efficiency, all of which contribute to further raising greenhouse gas emissions. (Yosef dejene, 2004).
MCF is dedicated to reducing the effects of its production activities on the environment and to manufacturing cement in an economical and environmentally responsible manner. MCF has identified and assessed the primary causes and effects of environmental impacts through the use of a multi-criteria analysis in an environmental impact study (Unknown, Messebo cement, 2015).

According to the report by (Assefa Berhe, 2014), the factory's clinker production and raw material and coal preparation are the main causes of environmental consequences. The study also discovered that heat loss, noise, odor, dust emissions, and storm water runoff have the biggest effects on the environment. The local environment and neighboring people are impacted in terms of livelihood, health, and the quality of the air, water, and soil (Assefa Berhe, 2014).

MCF has implemented a number of strategies to mitigate and avoid the negative effects of its industrial processes on the environment. Installing dust collectors and filters to reduce dust emissions from raw material and coal preparation facilities, as well as clinker production units, is one of these approaches (Assefa Berhe, 2014).

Putting sound insulation, silencers, and mufflers to use in order to lower the noise levels coming from the kiln and cooler fans, as well as the crushing and grinding machinery (Assefa Berhe, 2014).

Utilizing odor-control techniques to eliminate sulfur dioxide (SO2) and volatile organic compounds (VOCs) from kiln exhaust gases, such as chemical scrubbers and activated carbon filters. Producing power and hot water for the factory and the surrounding people by recovering waste heat from the kiln and cooled exhaust gasses(Unknown, Messebo cement, 2015).

Building sedimentation ponds and storm water drainage systems to gather and clean industry runoff water, stop soil erosion, and stop pollution of the water supply. Encouraging, educating, and training staff members to do activities in an ecologically responsible manner and to adhere to all applicable environmental laws and regulations is vital (Assefa Berhe, 2014).

Monitoring and assessing the factory's environmental performance and compliance through regular environmental audits and assessments. In addition, MCF engages in several social responsibility and community development initiatives, including job creation, bolstering health and education services, and supporting local communities' cultural and sporting activities.(Assefa Berhe, 2014).

High temperatures in the kilns are necessary for clinkerization, the principal source of CO2 emissions from the cement industry, during the energy-intensive cement manufacturing process (Oluwafemi et al, 2021).

By replacing conventional fuels like coal and petroleum coke with alternative fuels like biomass, waste, and natural gas, the cement industry may reduce its energy consumption, greenhouse gas emissions, fuel pricing, and waste management. Alternative fuel use does, however, come with certain drawbacks, including issues with quality, availability, handling, storage, safety, and compatibility with current machinery and procedures. Furthermore, some alternative fuels may emit more dioxins, heavy metals, sulfur oxides, and nitrogen oxides than others, which calls for careful monitoring and control. Furthermore, some alternative fuels may emit more dioxins, heavy metals, sulfur oxides, and nitrogen oxides than others, which calls for careful monitoring and control (Oluwafemi et al, 2021).
The selection of fuel for cement production is influenced by many variables, including the cost and availability of the fuels locally, the kilns' energy efficiency and environmental performance, the policies and incentives surrounding the use of alternative fuels, and the viability of co-processing different fuels from a technical and financial standpoint (Oluwafemi et al, 2021).

One kilogram of green cement clinker requires roughly 570 kilocalories of thermal energy to create, which is less than the 720 kilocalories of heat energy needed to produce one kilogram of Portland cement, according to a study by Oluwafemi et al. (2021). This lowers CO2 emissions by 2% and energy usage by 20% (Oluwafemi et al, 2021).

In a natural gas-fired cement factory, the use of 50% alternative fuels can lower fuel costs by 25% and CO2 emissions by 10% when compared to utilizing exclusively natural gas, per a study by Oluwafemi et al. (2021).

If the technological, financial, and environmental obstacles are removed, the use of waste and biomass as alternative fuels in the Chinese cement industry has the potential to save 130 million tons of coal equivalent and cut 340 million tons of CO_2 emissions annually (Murray, 2008).

As a result, it is determined that a way to switch the fuel source is essential. This study will evaluate the viability of using sawdust and co-fired coal in place of coal at the Messebo Cement Factory.

1.1. Background

Messebo Cement Factory Line-1:

There are two cement production lines at the Messebo Cement Factory, which is situated in Mekelle City, in the northern region of Ethiopia, 762 kilometers from Addis Ababa, the country's capital. The new second line can handle 3000 tpd of clinker in design capacity, whilst the first line can handle 2000 tpd. As a case study, the old line with a design capacity of 2000T per day of clinker is examined in this research. The Φ3.75x57m with inline calciner (ILC precalciner) and a single five-step preheater make up the kiln burning system.

The kiln system is currently operating at up to 2500T/day with considerable optimization, despite being intended for 2000T/day. The system's average planned specific heat consumption is between 710 and 750 kcal/kg of clinker. The $CaCO_3$ calcination rate in the kiln inlet can reach 95% after the raw meal has been warmed in preheater stages from 1 to 5 and precalcined in pre calciner. Inside the kiln, the final 5% of the calcinations and 100% of the clinkerization process will take place. In the pre calciner and kiln used for clinkerization, the ratio of burning coal to fire oil is 4:6 (Axumawi Ebuy Teka, 2015).

The main source of fuel for the Messebo Cement business, coal, is costly and must be supplied from abroad, which is why it is having trouble. They use only 4 percent of their sesame husk supply; imported coal is used to meet their fuel needs. The plant can calcine 3,000 tons of clinker a day thanks to its 6-stage pre-heater, pre-calciner, rotary kiln, and grate cooler. Roughly 3,260.4 MJ of energy is consumed every ton to make clinker.

This procedure adds a substantial amount of expense to the production of cement, mostly because imported coal is used. Usually, 40% of the coal is added to the burner of the main kiln and 60% of the coal is placed into the clinker pre-calciner. The energy required to produce clinker varies depending on the technique employed. The least energy-intensive method is the wet process with internals, which requires 6.8 MJ/kg of clinker production; the dry method uses less energy, requiring less than 2.93 MJ/kg of clinker production. This kind of energy-efficient kiln method falls under the 6-stage calciner plus preheater category, which is equipped with a high-performance hot clinker cooler(Rahman, 2015).

Cooler fans use a type of grate cooler to cool clinker. The cooler's integrated hammer crusher crushes the clinker before bucket (or pan) conveyors transport it to the clinker storage area. Part of the cooler's output gas is sent as secondary air to the kiln and part of it is sent as tertiary air to the calciner. A scrubber and an electrostatic precipitator are used to cool and purify the excess material before it is released into the environment.

In general, the substitution of alternative renewable resources will have an attractive benefit. Ethiopian cement industries must develop to burn alternative fuels in their kilns in order to provide a viable and convenient end-of-life option for byproducts and wastes and also to achieve their main strategic plan of climate reliance and green economy in 2025. (Axumawi Ebuy Teka, 2015).

1.2. Statement of the Problem

The statement of the problem underscores several critical challenges confronting Ethiopian cement industries, notably their heavy reliance on conventional fossil fuels, especially from foreign sources like coal and heavy petroleum oil. The escalating costs of these fossil fuels, their non-renewable nature, and their substantial contribution to global warming, marked by high CO2 emissions, necessitate a shift towards alternative and renewable energy sources.

Messebo cement factory's current reliance on costly and environmentally harmful South African coal and pet coke exacerbates economic and environmental concerns. Moreover, the disposal methods for byproducts, such as sawdust, present environmental issues, with sawdust either being discarded into rivers or left to rot in fields due to the absence of viable alternative uses.

The identified limitations in the use of conventional fossil fuels and the unexploited potential of byproducts as alternative fuel sources underscore the imperative for this research initiative. The proposed solution involves the co-firing of sawdust and coal in cement kilns, a process that combines the two as fuel for cement production. The rationale for exploring this approach is multifaceted and includes the following benefits:

1.2.1. **Cost Reduction:** The incorporation of sawdust, an abundant and cost-effective biomass resource, offers the potential to significantly decrease operating costs compared to relatively expensive coal.

1.2.2. **Environmental Benefits:** Co-firing of sawdust and coal has the potential to limit the need for landfilling, and the renewable and carbon-neutral nature of sawdust can offset greenhouse gas emissions from coal combustion. Additionally, the process can reduce emissions of SOx, NOx, and particulate matter, contributing to environmental sustainability.

1.2.3. **Design Benefits:** With very little adjustments, the co-firing technology can be easily incorporated into already-existing cement kilns. Control over the co-firing process is improved by the ability to feed sawdust either separately or in conjunction with coal, enabling modifications based on clinker quality needs and kiln conditions.

Furthermore, sawdust's increased reactivity and lower ignition temperature can enhance flame stability and combustion efficiency.

Notwithstanding these benefits, there are still issues and restrictions that need to be resolved before widespread adoption. These include concerns about sawdust quality and availability, possible effects on kiln performance and clinker quality, safe sawdust handling and storage practices, and adherence to safety and regulatory requirements

A comprehensive consideration of these aspects is essential for the successful integration of the co-firing process, aligning economic and environmental objectives in the Ethiopian cement industry. The research aims to provide a nuanced and pragmatic solution that balances the need for cost-effectiveness with environmental sustainability.

1.3. Objectives

1.3.1. General objective

To examine possible fuel switching options for the pyro processing of cement via co-firing sawdust and coal.

1.3.2. Specific objectives

The specific objectives of the project were:

- To achieve greenhouse gas emission reductions through the partial substitution of fossil fuels with alternative fuels in cement plants.
- To determine the flame temperature of the co-firing of a mixture of sawdust and coal in contrast with coal alone in the kiln for clinker production.
- To evaluate the environmental, economic, and technical advantages of using co-fired sawdust and coal as fuel sources in comparison with coal alone.

1.4. Significance of the research

This study has wider ramifications for Ethiopia's cement sector as a whole as well as for society at large, going beyond the specific context of the Messebo cement factory. Co-processing wastes and byproducts to create alternative fuels has several advantages that support economic viability, energy security, and environmental sustainability.

1.4.1. Environmental Impact:

This research stands as a pivotal initiative in mitigating greenhouse gas emissions within the cement industry. By optimizing clinker production through the co-processing of byproducts and wastes, it directly addresses environmental concerns. The reduction in greenhouse gas emissions aligns with global efforts to combat climate change and positions Ethiopia to fulfill its strategic goal of transitioning to a climate-resilient green economy.

1.4.2. Sustainable Energy Security:

The study presents a viable approach that optimizes the extraction of energy from garbage. A certain level of energy security is gained by the cement industry through the co-firing process, which uses alternative fuels like sawdust. In contrast to traditional fossil fuels that are prone to fluctuations in worldwide prices, waste-derived fuels are almost always available. This serves as a buffer against the volatility of the world energy market in addition to enhancing the sustainability of energy sources.

1.4.3. Waste Disposal and Environmental Stewardship

A critical aspect of the research is its positive impact on waste disposal. Co-processing byproducts such as sawdust not only provides a practical fuel solution but also addresses the challenging task of waste disposal in an environmentally sound manner. This aligns with principles of environmental stewardship, promoting a circular economy where waste materials are repurposed rather than discarded.

1.4.4. Economic Benefits:

The economic benefits of changing fuels, especially to alternative fuels, are significant. For cement producers, the lower cost of fuels directly results in financial savings. This strategy is also more economically appealing since it has the potential to generate additional cash through Clean Development Mechanism (CDM) programs, which incentivize the reduction of CO2 emissions. At the national level, these financial advantages result in potential for job creation and saves on foreign exchange, which boosts the whole economy.

1.4.5. Aligned with National Goals:

The research aligns seamlessly with the national objectives outlined in Ethiopia's strategic plan for a climate-reliant green economy. By offering a viable and sustainable alternative to conventional fuel sources, the research contributes to the realization of national goals related to environmental sustainability, economic development, and energy security.

In conclusion, this research carries profound significance by presenting a holistic and forward-thinking solution that addresses environmental, economic, and energy challenges faced by the cement industry in Ethiopia. The potential ripple effects extend to the broader societal and national levels, making it a strategic and impactful endeavor.

2. LITERATURE REVIEW

2.1. Overview of cement production

Today, the main type of cement is Portland cement, which mainly consists of di- and tricalcium silicates. When the Portland cement is mixed with water it hydrates and hardens to bind together the stone and gravel in the concrete (G. C. Bye, 1999).

But there are problems with using Portland cement clinker so much. According to the US Geological Survey (2018), 4.1 billion tons of cement were produced worldwide in 2017, and the cement sector is accountable for 5% of global CO2 emissions.(K. A. Baumert, 2005).
In addition, the production of cement requires a significant amount of energy, with the average global thermal energy usage being approximately 4.2 GJ/ton clinker, whilst the most efficient plants use 2.9 GJ/ton clinker. (IEA, 2009). This leads to high fuel expenditures, which often account for 30–40% of the cost of producing cement (E. Mokrzycki and A. Uliasz- Bochenczyk, 2003).
A Synopsis of Cement Manufacturing In Ethiopia, there were eight operational cement plants in 2010, and twelve more that were being built. It is anticipated that the new plants will start up in 2012 and run until 2016. In addition to the major cement companies that already exist in Ethiopia, like Mugher Cement, Derba Cement, and National Cement Factory, there are currently new players entering the market. Clinker-to-cement ratio, or clinker production divided by cement production, was 0.85 in 2010 based on survey estimates of actual cement and clinker production of 2.0 Mt and 1.7 Mt, respectively.(Tesema, 2015).
In emerging nations, cement plays a critical role in both economic growth and the fight against poverty. Cement is a crucial component of concrete, along with aggregates and water, and as such, it is a building material that is required for large-scale energy, water, and transportation infrastructure projects as well as—most importantly—the construction of contemporary buildings and urban infrastructure(IFC, 2017).

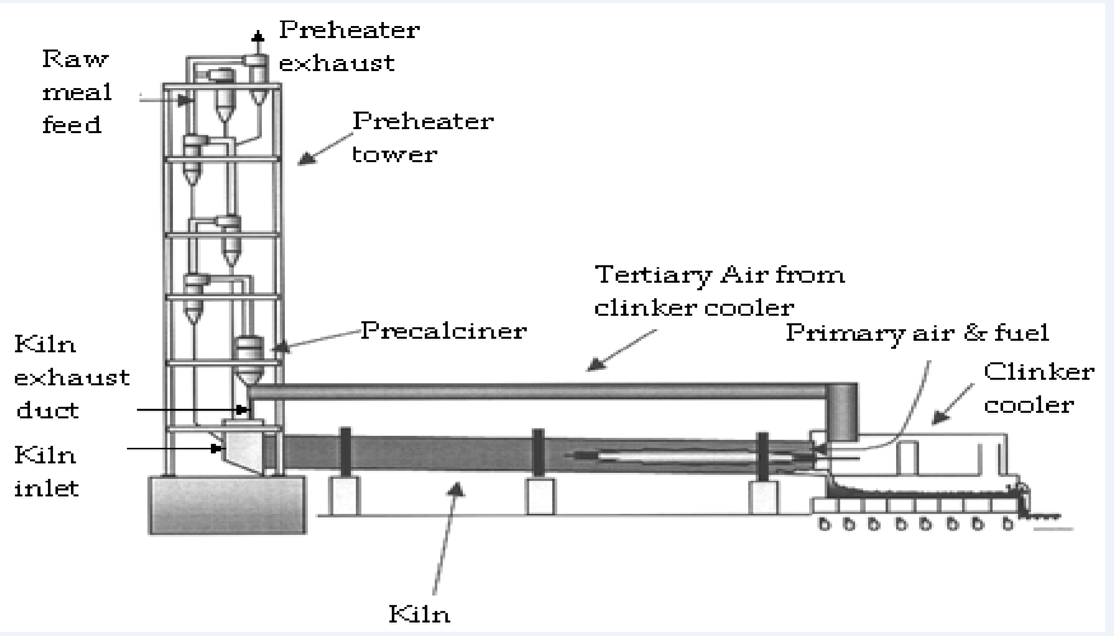


Figure 1 Schematic of cement production

2.2. Details of Cement Production Process

Cement production begins with the procurement of raw materials, which includes blasting rocks, dumping trucks carrying the raw material from quarries, on-site crushing of the rock, and conveyor belts carrying it to the cement factory. The plant storage facilities store and homogenize the raw materials that are brought to the plant. The homogenized raw material is ground to produce the raw meal. The uncooked food is transferred to the kiln after being preheated in cyclone heaters and calcined. (Seboka et al, 2009).

There are two kinds of kilns used in the manufacture of cement. These are the large-scale horizontal rotary kilns that are commonly used in developed countries, and the small-scale vertical kilns that are mostly utilized in developing nations. Rotary kilns of a larger size use less energy. The raw material is heated to roughly 1,500°C in the kiln by a flame that is 2,000°C. Clinker is produced following air cooling. Clinker, the main component used to make cement, is mostly composed of clay and limestone, about 80% by weight. There are four steps in the clinker forming process (Karstensen K.H, 2006).

The process of making cement involves two steps. Firstly, a rotary kiln is used to heat raw materials (calcium oxide, 65%), silicon oxide, 20%, alumina oxide, 10%, and iron oxide, 5%), to temperatures as high as 1,500°C in order to generate clinker. The method for this phase can be wet, semi-wet, dry, or semi-dry depending on the raw material's condition. The second phase is adding gypsum (calcium sulfates) and sometimes other minerals, like coal fly ash and natural pozzolanas, to the clinker after it has been created (Thrän, 2017).

The following table 2 lists the primary cement raw ingredients and their corresponding sources.

Raw materials	**Sources**
Lime (CaO)	Limestone, Shale, Marl
Silica (SiO_2)	Sand, Clay, Shale, Marl
Alumina (Al_2O_3)	Clay, Shale, Slag
Iron Oxide (Fe_2O_3)	Iron Ore, Clay, Mill Scale
Trace Sulfate (SO_3)	Gypsum

Table 2 Raw materials for cement production

The cement manufacturing process involves the following steps.

a) Mixing and crushing of raw materials - limestone, clay, silica sand, and iron material,
b) Feeding the raw meal thus obtained into a rotary kiln, burning a large amount of fuel, and sintering at a temperature of about 1450°C to obtain clinker,

c) Addition of gypsum and pulverizing of the mixture.

d) Packaging and storage

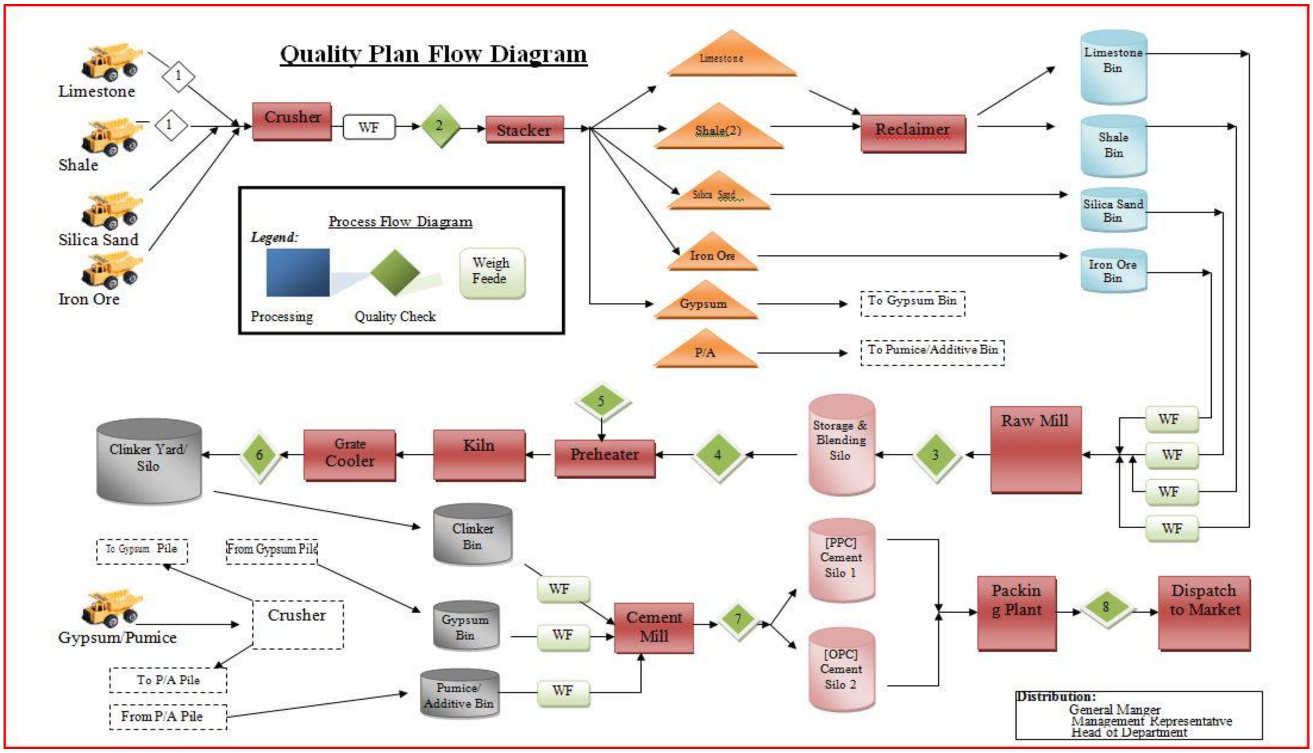


Figure 2 flow diagram of cement production

The process of turning raw materials like limestone, clay, and sand into cement—a necessary component of concrete—is known as the cement manufacturing process. Cement production is a multi-step process that includes quarrying, crushing, grinding, pyro processing, cooling, and packing. Every stage has a significant impact on the final product's functionality and quality. This is a quick synopsis of the steps involved in making cement:

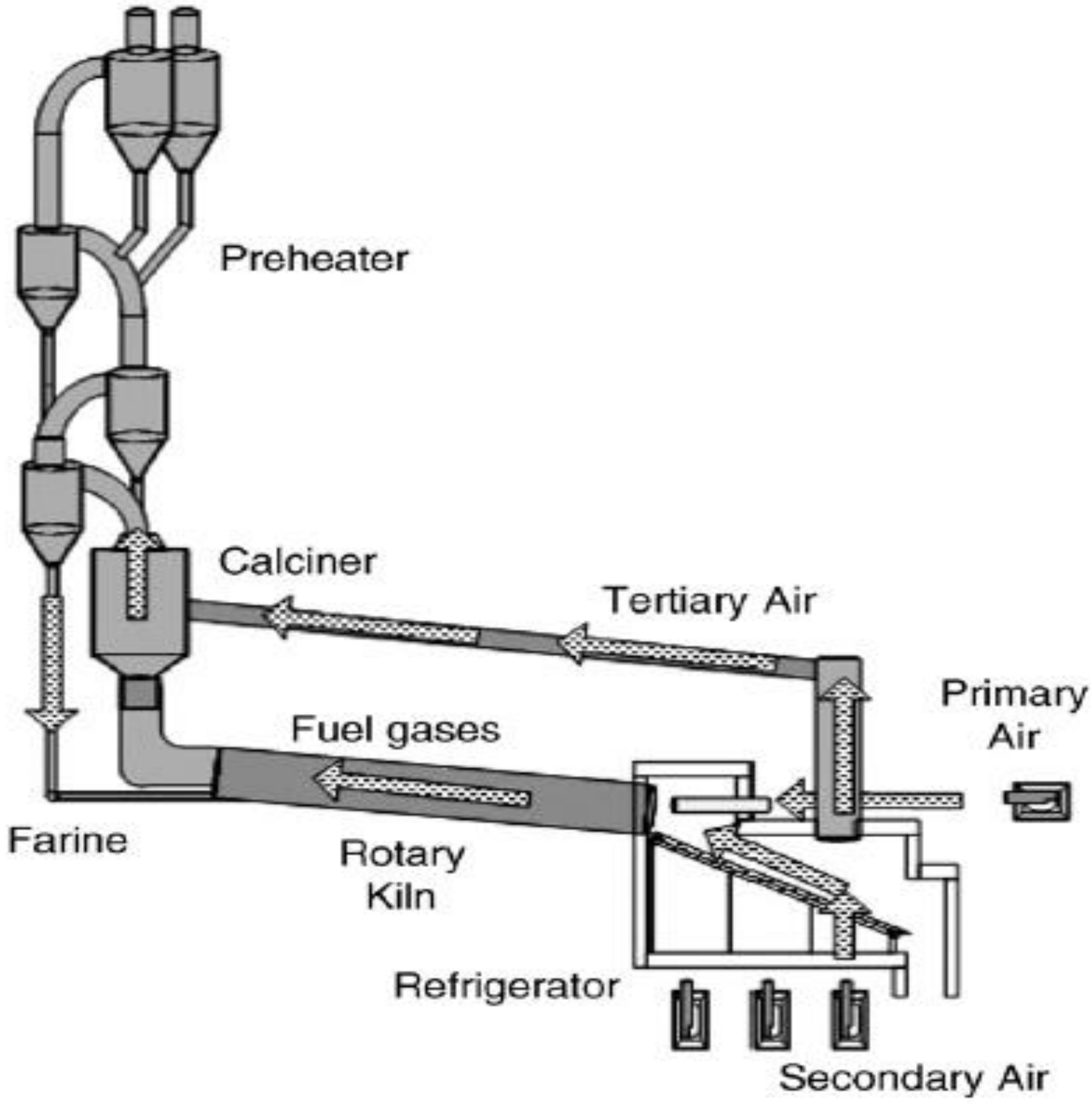


Figure 3 Schematic diagram of cement manufacturing

- *Quarrying*: Extracting the earth's raw minerals is the first stage. Limestone, which gives calcium oxide, and clay or shale, which provide silicon, aluminum, and iron oxides, are the primary raw materials used to make cement. Additional elements including fly ash, gypsum, iron ore, and sand can be added to modify the raw mix's chemical makeup. After being extracted from the quarry by blasting, drilling, or excavation, the raw materials are normally moved to the crusher facility.
- *Crushing:* To prepare the raw materials for grinding, the second stage is to minimize their size. The raw materials are fed into primary and secondary crushers, which reduce their size into smaller bits by impact, compression, or shear forces. Following their crushing, the materials are filtered and kept in bins or silos (seyda tehsin, 2014).

- *Grinding:* The raw components are ground into a fine powder known as raw meal in the third phase. In order to get the correct chemical composition of the cement, the raw components are combined and proportioned. In a raw mill, which is a big spinning drum with steel rollers or balls within, the raw meal is subsequently dried and processed. Depending on the raw materials' moisture level, the raw mill can run in either a wet or a dry mode. After that, the uncooked food is kept in a homogenization silo, where it is mixed and given air to guarantee consistency(seyda tehsin, 2014) .
- *Pyro processing:* The raw meal is heated to a high temperature in the fourth phase, which is where it undergoes physical and chemical changes to generate clinker, which is the primary ingredient in cement. The kiln's hot exhaust fumes prehecate the raw meal as it is fed into a preheater tower. The raw food is taken out of the gas and moved to the next level of the preheater tower, which is made up of many cyclone stages. After being heated, the raw meal is supplied into a precalciner, where some of the fuel is burned and the cooler's tertiary air is used to calcine the food. After being calcined, the raw meal is fed into a rotary kiln, a long, cylindrical furnace that revolves between one and five revolutions per minute. Refractory bricks are used to line the rotary kiln in order to shield it from the high temperature and chemical reactions. There are four zones in a rotary kiln: cooling, clinkerizing, calcining, and drying. The moisture in the raw food evaporates in the drying zone.In the calcining zone, the calcium carbonate in the raw meal decomposes into calcium oxide and carbon dioxide. In the clinkerizing zone, the calcium oxide reacts with the other oxides to form the four main minerals of clinker: alite, belite, aluminate, and ferrite. In the cooling zone, the clinker is cooled by the secondary air from the cooler. The clinker is then discharged from the kiln and transported to the cooler The calcium carbonate in the raw meal breaks down into carbon dioxide and calcium oxide in the calcining zone. The four primary minerals of clinker are aluminate, ferrite, belite, and alite, which are formed when calcium oxide combines with other oxides in the clinkerizing zone. The secondary air from the cooler cools the clinker in the cooling zone. After that, the clinker is moved to the chiller after being released from the kiln (seyda tehsin, 2014).
- *Cooling:* To maintain the quality and qualities of the clinker, the fifth stage involves cooling it quickly. Clinker is supplied into a grate cooler, an apparatus that moves the clinker from the intake to the output using a number of moving grates. The ambient air that is forced through the grates cools the clinker. After cooling, the clinker is placed in a clinker silo to await grinding. Additionally, the cooling air serves as the kiln's secondary air and the precalciner's tertiary air (seyda tehsin, 2014).
- *Grinding:* Cement is made by grinding the clinker into a fine powder in the sixth stage. In order to enhance the qualities and functionality of the cement, additional additives like fly ash, slag, or pozzolana are combined with the clinker. Gypsum serves as a set retarder. After that, the cement is pulverized in a cement mill, which is a sizable revolving drum outfitted with steel rollers or balls. Depending on the cement's moisture content, the cement mill can run in either a wet or a dry mode. After that, the cement is mixed and tested in a cement silo to make sure it is consistent (seyda tehsin, 2014)
- *Packing:* Packing the cement into bags or bulk containers for sale and distribution is the last stage. From the cement silo, the material is transported to the packing facility, where it is weighed, packed into bags, and then loaded onto trucks or ships. The 50 kg or 100 lb cement bags are often composed of paper or plastic. The bulk cement containers typically consist of steel or concrete and can hold many tons of material (seyda tehsin, 2014).

2.2.1. Pyro processing in cement production

The pyro-processing stage in cement production is the process of heating the raw materials to a high temperature, where they undergo chemical and physical changes to form clinker, the main component of cement. The pyro-processing stage is important for several reasons::

- It establishes the final product's strength, durability, and performance, among other qualities.
- The clinker's chemical and mineralogical composition is impacted by the pyro-processing stage, which subsequently influences the cement paste's hydration and hardening.
- In the process of making cement, it uses the greatest energy and produces the most greenhouse gases. About 90% of the energy used and 80% of the carbon dioxide emissions in the cement industry come from the pyro-processing step. Thus, increasing the pyro-processing stage's efficiency and lowering its emissions can have a major positive impact on the environment and the economy.
- It offers opportunities for innovation and optimization in the cement production process.
- The pyro-processing phase can be adjusted or improved by the use of various kiln types, fuels, additives, raw materials, and technologies.
- For instance, cofiring trash or biomass with coal can lower the amount of fossil fuel used in the pyroprocessing stage as well as the carbon dioxide emissions. Similar to this, employing substitute raw materials like fly ash, slag, or pozzolana can enhance the characteristics and functionality of cement while lowering the clinker factor and pyro-processing stage's energy consumption. (Jackson Muthengia Wachira, 2020)

2.2.2. Traditional fuels in cement production

Fossil fuels, including coal, oil, petroleum coke, and natural gas, are the primary fuels utilized in the conventional cement manufacturing process. These fuels are used to produce the energy and high temperature needed for the pyroprocessing step, which turns the raw materials into clinker, which is the primary ingredient in cement. About 90% of the fuel used and 80% of the carbon dioxide emissions in the cement sector come from fossil fuels.(somer, 2020).

The primary environmental consequences linked to conventional fuels are resource depletion, air pollution, and greenhouse gas emissions. Carbon dioxide, which is emitted during the burning of fossil fuels and the calcination of limestone, makes up the majority of greenhouse gas emissions. Emissions of carbon dioxide are a contributing factor to climate change and global warming, which may have detrimental consequences on biodiversity, ecosystems, and human health. The primary causes of air pollution are particulate matter, sulfur dioxide, and nitrogen oxides, which are released during the clinkerization process and the burning of fossil fuels.

Smog, respiratory illnesses, acid rain, and other air pollution can harm people's health as well as structures and agriculture. The primary cause of resource depletion is the exhaustion of non-renewable fossil fuels, which have a limited and finite supply. The social welfare, economic stability, and energy security of the nations that rely on fossil fuels can all be impacted by resource depletion. (Unknown U. , 2013). As a result, there are serious environmental effects from the use of traditional fuels in cement manufacture that must be considered and minimized.

- Increasing energy efficiency and optimizing the cement production process can lower emissions and fuel consumption per unit of output, which are two potential strategies to lessen the environmental effects. (somer, 2020).
- Utilizing substitute or additional energy sources, including waste, biomass, or hydrogen, to offset fossil fuel consumption and lower cement production's carbon footprint and emissions.
- The adoption of carbon capture and storage or utilization technology can stop carbon dioxide emissions from cement manufacturing from entering the atmosphere by capturing, storing, or utilizing them(Unknown U. , 2013)
- Creating and utilizing low-carbon cements that can lower the clinker factor and cement production emissions, like blended cements, geopolymer cements, or calcium sulfoaluminate cements. The main environmental effects of using traditional fuels in cement kilns are connected to the emissions of various pollutants including arsenic (As) and sulfur dioxide (SO2), as well as greenhouse gasses like carbon dioxide (CO2). In cement kilns, the burning of fossil fuels accounts for roughly 40% of CO2 emissions, with the remaining 10% coming from indirect emissions from the use of electricity, mostly for grinding raw materials and cement. This information is based on data from Wojtacha-Rychte (2021). Improving CO2 emissions is a critical challenge for the cement industry as it contributes significantly to climate change and global warming.

Utilizing alternative fuels, which have a higher calorific value and a lower carbon intensity than conventional fuels like coal and petroleum coke, such as tires, industrial waste, and biomass, is one method to achieve this.

In addition to lowering cement production costs, alternative fuels can minimize waste output and the use of natural resources. Alternative fuels do, however, also present certain socio-environmental difficulties, including the possibility of contamination, the requirement for safe handling and storage, the possibility of higher emissions of other pollutants, and the potential influence on the cement's performance and quality. In order to make sure that the advantages of using alternative fuels in cement kilns outweigh the dangers and expenses, rigorous consideration, monitoring, and regulation are necessary. Alternative fuels can be utilized in cement kilns safely and productively without sacrificing technical or environmental criteria, according to certain studies. (Wojtacha-Rychte, 2021)

For instance, a study by Boey (2017) discovered that, in comparison to utilizing coal, using waste tires as fuel in cement kilns can cut CO2 emissions by 27%, NOx emissions by 9%, and SO2 emission. (boey, 2017)

In a different study, the burning of arsenic-contaminated vulcanized rubber was simulated (Wojtacha-Rychte, 2021). It was discovered that the arsenic was totally eliminated during the high-temperature process, resulting in the production of SO2 and As_2O_3, which may be collected and handled by the current emission control systems. These studies also show that more investigation and development are necessary to solve the remaining issues and uncertainties and to maximize the usage of alternative fuels in cement kilns (Wojtacha-Rychte, 2021).

2.3.1. Overview of alternative fuels

Fuels obtained from non-petroleum sources are known as alternative fuels, and they have the potential to lessen reliance on fossil fuels and the greenhouse gas emissions they produce. Several popular substitute fuels consist of:

Biomass: is the organic material that undergoes different processes to transform into solid, liquid, or gaseous fuels. Wood, agricultural waste, animal feces, algae, and other materials can all be considered forms of biomass, which can be derived from plants, animals, or microbes. Biofuels including ethanol, biodiesel, biogas, and bio-oil can be produced from biomass, along with bio-based goods and chemicals.

Waste-derived fuels: are fuels made from waste streams that would normally be disposed of in landfills or incinerators, such as industrial waste, municipal solid waste (MSW), or other waste streams. Refuse-derived fuel (RDF), a solid fuel derived from the portion of MSW that is combustible; syngas, a gaseous fuel generated through gasification of MSW or biomass; and landfill gas, a gaseous fuel obtained from the anaerobic breakdown of organic waste in landfills are examples of waste-derived fuels.

2.3.2. Other alternative fuels

Include gaseous fossil fuels such as propane, natural gas, methane, and ammonia; alcohols such as ethanol, methanol, and butanol; vegetable and waste-derived oils; and other renewable fuels such as hydrogen and electricity (Wilfred and ibrahim, 2019). . These fuels can be used for various applications, such as transportation, heating, power generation, etc.

The benefits and drawbacks of alternative fuels vary based on their sources, processes of production, availability, cost, efficiency, and effects on the environment. As a result, the selection of alternative fuels is influenced by a number of variables, including feedstock availability, compatibility with current vehicles and infrastructure, laws and incentives, and customer preferences. The switch to a low-carbon and sustainable energy system can be aided by alternative fuels, but there are a number of obstacles and difficulties that must be overcome, including institutional, social, economic, and technical problems (Wilfred and ibrahim, 2019).

2.3.4. Criteria for using alternative fuel

Since alternative fuels are a blend of different wastes, they need to meet specific requirements. To guarantee environmental protection, the fuel's chemical composition must adhere to legal requirements. Its calorific value needs to be higher than a particular threshold. The composition of the fuel should be somewhat uniform.

The physical form must allow easy handling for transportation. It should be economically viable along with its availability. The energy, ash, moisture and volatiles contents of the fuels should be given an important consideration.

For alternative fuels, a flexible fuel feeding system must be created to prevent feeding-related issues.It is anticipated that the following characteristics will make them alternative fuels (Kaddatz et al, 2013).

- ➢The physical state of the fuel (solid, liquid, gaseous)
- ➢The content of circulating elements (Na, K, Cl, S)
- ➢Toxicity (organic compounds, heavy metals)
- ➢Composition and content of ash, Content of volatiles
- ➢Calorific value (over 14.0 MJ/kg)
- ➢Chlorine content (less than 0.2%)
- ➢Sulfur content (less than 2.5%)
- ➢PCB content—less than 50ppm
- ➢heavy-metals content—less than 2500ppm [out of which: mercury (Hg)—less than 10ppm, and total cadmium (Cd), thallium (Tl) and mercury (Hg)—less than 100ppm].
- ➢Physical properties like scrap size, density, homogeneity, grinding properties, moisture content
- ➢proportioning technology
- ➢the emissions released
- ➢the cement quality and its compatibility with the environment must not decrease,
- ➢Alternative fuels must be economically viable

2.3.5. Previous studies on co-firing in cement kilns

The practice of employing alternative fuels (AFs) in cement kilns alongside traditional fuels like coal or petcoke is known as co-firing. AFs can come from a variety of sources; including tires, biomass, industrial waste, and municipal solid waste (MSW). Co-firing can lower the operational costs and the impact cement manufacturing has on the environment, but it also comes with risks and problems for the kiln's performance and the quality of the clinker. As a result, many academics and industry professionals are interested in co-firing in cement kilns.

The effects of cofiring on kiln performance and emissions, the types and characteristics of AFs, the combustion behavior and flame characteristics of AFs, the modeling and simulation of cofiring processes, and the optimization and control of cofiring systems are just a few of the topics covered in the numerous studies on cofiring in cement kilns. Among the most current research are:

- ❖ (Sharma et al, 2022) Examined the state of affairs and difficulties surrounding the co-processing of refuse-derived fuel (RDF) in the manufacturing of cement, and contrasted the direct burning of RDF in a kiln or calciner with the process integration of RDF gasification. They outlined the benefits and drawbacks of both strategies and stressed the necessity of creating appropriate models for forecasting the calciner output depending on various RDFs (Sharma et al, 2022).
- ❖ Wojtacha-Rychte has out a multi-case research on the financial and environmental advantages of cofiring RDF in Polish cement kilns. After examining the life cycle assessment (LCA) and life cycle costing (LCC) of four scenarios with varying ratios of RDF substitution, they

discovered that co-firing RDF can lower cement manufacturing costs and greenhouse gas emissions (Wojtacha-Rychte, 2021) (2021).

- (Jones, 1980) Presented the findings of a study that looked into RDF's potential use in a US cement plant's kiln fuel. The project included testing RDF co-firing with coal, modifying the kiln burner, and designing and installing an RDF feed system. The project showed that RDF can be co-fired in cement kilns successfully and that there are no negative effects on emissions or product quality (Jones, 1980).
- In 2018, Pedersen presented his doctoral thesis on the co-firing of alternative fuels in the burners of cement kilns. He created a model to explain the combustion in the cement kiln and carried out practical research at full-scale cement factories to look into the impact of co-firing on the kiln flame. In addition, he described the physical, chemical, and combustion characteristics of the alternate fuels (Pedersen, 2018) .
- Based on a study of current knowledge and experience, Sharma et al. (2022) published a paper on the co-utilization of coal and other fuels in cement kilns. The types and traits of various AFs, co-firing trends and drivers in various locations, co-firing problems and benefits, and co-firing best practices and recommendations were all compiled in this paper (Sharma et al, 2022).

2.3. Benefits and Limitations of Co-Firing

Co-firing, which is the simultaneous burning of many fuels in one combustion system, is a common technique used in the pyroprocessing of cement kilns to add alternative fuels in addition to conventional fossil fuels. The following are the specific advantages and drawbacks of co-firing in cement kiln pyroprocessing:

2.3.1. Benefits

Cofiring coal and biomass has various advantages for the environment. Lowering CO2 emissions is one of the advantages. The quantity of CO2 absorbed by biomass during its growing cycle is equal to the amount of CO2 released upon burning. Consequently, when biomass is co-fired with coal, the net CO2 released is almost zero, and this will demonstrate a decrease in CO2 emissions by mass. (Lacrosse L., Mathias A. J, 2004)

2.3.1.1. Reduced Carbon Footprint

Co firing with alternative fuels, including biomass or fuels sourced from waste, can assist in lowering the cement production's carbon footprint. When compared to conventional fossil fuels, these alternative fuels are frequently seen as carbon-neutral or having a lower carbon content.

2.3.1.2. Waste Utilization:

Co-firing provides an opportunity to use waste materials as alternative fuels, contributing to waste reduction and helping to address environmental concerns associated with waste disposal. Common waste-derived fuels include municipal solid waste, tires, and sewage sludge.

2.3.1.3. Cost Savings:

Since some alternative fuels may be more cost-effective than conventional fossil fuels, using them in co firing could result in cost savings for cement producers.

2.3.1.4. Energy Recovery:

Co-firing makes it possible to recover energy from waste materials that would otherwise be thrown away, which improves cement production's sustainability and energy efficiency.

2.3.1.5. Diversification of Energy Sources:

Cement plants can increase energy security and lessen their reliance on a single fuel type by diversifying their energy sources through co-firing.

2.3.1.6. Compliance with Regulations:

Because co firing with alternative fuels lowers emissions and shows a commitment to sustainable practices, it can assist cement factories in adhering to environmental requirements.

Stable Energy Supply: Co firing helps reduce the effects of price volatility and fluctuations in fuel supply by combining many fuel sources to produce a more steady and dependable energy supply.

2.3.2. Limitations

2.3.2.1. Technical Challenges:

Co-firing may present technological difficulties with regard to control systems, fuel handling, and combustion efficiency. Certain alternative fuels have unique combustion properties that call for kiln operating modifications.

2.3.2.2. Quality Variability:

The quality and composition of alternative fuels might vary, particularly those sourced from trash. Variations in fuel quality can affect product quality, kiln performance, and combustion efficiency.

2.3.2.3. Investment Costs:

Requiring a substantial capital expenditure, upgrading or altering current cement kilns to allow for co-firing may be necessary. For certain cement factories, the upfront expenses of adding safety precautions and modifying equipment can be prohibitive.

2.3.2.4. Emission Concerns:

Cofiring can lower carbon emissions, but it also has the potential to bring in pollutants or other emissions from the alternative fuels. Systems for effectively controlling emissions are required to handle possible environmental issues.

2.3.2.5. Logistical Challenges:

Purchasing, transporting, and storing alternative fuels may necessitate adjustments to supply chain management and logistics in order to implement co-firing.

2.3.2.6. Regulatory Compliance:

restrictions controlling the use of alternative fuels can be difficult to comply with, and co-firing methods may not be feasible if restrictions change.

2.3.2.7. Public Perception:

The kind of alternative fuels utilized may make it difficult for the public to accept them. Concerns about certain waste-derived fuels' smell, aesthetic impact, and possible health and safety risks must be addressed by cement factories.

In conclusion, co-firing in cement kiln pyro processing has a number of positive effects on the environment and the economy, but cement producers must carefully assess and deal with the operational, technical, and legal issues that arise when co-firing techniques are used.

2.3.3. Introduction to Various Technologies of Co-Firing

In co-firing technologies, many fuels are burned simultaneously in a single combustion system. Different technologies are used in cement kiln pyro processing to make it easier for conventional fossil fuels and alternative fuels to be co-fired. An overview of some of the major technologies utilized in co-firing is provided below.

2.3.3.1. Grate Firing:

The process of burning solid fuels, such as biomass and fuels obtained from waste, on a stationary grate is known as "grate firing." The combustion zone is gradually traversed by the fuel bed.

Application: Wood chips, agricultural leftovers, and solid refuse are good candidates for grate fires.

2.3.3.2. Fluidized Bed Combustion:

A bed of solid particles floating in an upward-flowing stream of air or another gas is known as fluidized bed combustion. Better mixing and combustion efficiency are offered by this technique for a variety of fuels, including waste and biomass.

Application: Fuels of different sizes and moisture contents can be burned using fluidized bed combustion because of its versatility.

2.3.3.3. Pulverized Coal Co-Firing:

In pulverized coal co-firing, alternative fuels are injected into the combustion chamber along with pulverized coal. Better combustion and effective fuel mixing are made possible by this approach.

Application: Pulverized coal co-firing provides flexible and effective combustion management, and is widely utilized in cement kilns and coal-fired power plants.

2.3.3.4. Rotary Kiln Co-Firing:

A rotary kiln is an essential part of the cement production process. By adding alternative fuels to the kiln system in addition to conventional fuels, usually through the main burner, co-firing can be accomplished.

Application: The simultaneous combustion of several fuels in the kiln is known as "rotary kiln co-firing," which is unique to the manufacturing of cement.

2.3.3.5. Fluidized Bed Gasification:

Description: Gasification is the process of combining solid fuels with a certain volume of oxygen or air to create a combustible gas. It is possible to co-fire the generated gas with conventional fuels.

Application: Solid waste or biomass can be gasified using a fluidized bed to create a syngas that can be co-fired in a variety of combustion systems..

2.3.3.6. Circulating Fluidized Bed (CFB) Combustion:

Fluidized bed combustion has been upgraded to become CFB combustion. It uses a solids-circulating loop to improve combustion efficiency and heat transfer.

Application: CFB combustion is utilized in power generation and industrial applications, and it may be applied to a variety of fuels, such as waste and biomass.

2.3.3.7. Direct Co-Firing:

Direct co-firing is a process wherein alternative fuels are directly injected into the combustion chamber in addition to conventional fuels. The fuel feeding rates for this technology need to be carefully controlled.

Application: In cement kilns, direct co-firing is a popular technique in which alternate fuels are introduced into the combustion chamber or kiln burner.

2.3.3.8. Indirect Co-Firing:

The process of gasifying alternative fuels outside of the combustion chamber and introducing the resultant gas into the primary combustion zone is known as indirect co-firing. Improved control over combustion conditions is possible with this technology.

Application: To increase combustion efficiency and lower emissions, indirect co-firing is used in a variety of combustion systems.

In sectors like cement production, where cutting carbon emissions and making the best use of resources are top concerns, co-firing technologies are essential to delivering sustainable and eco-friendly energy solutions. The selection of cofiring technology is contingent upon various aspects, including but not limited to fuel type, combustion characteristics, and the particular demands of the industrial process.

2.4. Fuel Utilizations in co firing

Co-firing is the process of burning more than one fuel in a combustion system at the same time. A variety of fuels can be used in co-firing situations across a range of sectors, including pyroprocessing in cement kilns. The selection of fuels is influenced by various aspects, including accessibility, expenses, ecological consequences, and the particular demands of the combustion process. The following are some typical fuel uses for co-firing.

Biomass:

Biomass is the collective term for organic materials originating from plants or animals, including wood, crop wastes, and crops grown specifically for energy.

Application: Because biomass is renewable and has a little carbon footprint, it is frequently employed in cofiring. It can take the shape of energy crops, sawdust, wood chips, or straw.

Coal:

Coal is a fossil fuel that has historically been burned in a number of different sectors.

Application: Cofiring is a popular technique in which alternative fuels are added to coal to lower carbon emissions and improve the combustion process' sustainability.

Municipal Solid Waste (MSW):

Household and commercial garbage are included in MSW, which can be processed to separate combustible materials for the creation of energy.

Application: In order to manage waste and recover energy, cofiring with fuels obtained from MSW is used in various industries, such as cement manufacture.

Tire-Derived Fuels:

Tire-derived fuels (TDF) are produced from processing tires and are utilized as a substitute fuel source.

Application: Cement kilns frequently co-fire with TDF. Because of their high calorific value, tires can help with energy recovery and lessen the environmental effect of tire disposal.

Industrial Wastes:

Alternative fuels can be derived from a variety of industrial wastes and by-products, including paper sludge, wasted solvents, and manufacturing leftovers.

Application: Cofiring with industrial wastes generates energy and offers a waste disposal solution that is environmentally friendly.

Biogas:

Anaerobic digestion of organic materials, such as sewage, animal dung, and agricultural waste, produces biogas.

Application: For enterprises looking for low-carbon and renewable fuel sources, cofiring biogas is an alternative. It is possible to introduce biogas straight into combustion systems.

Natural Gas:

Natural gas is a fossil fuel that burns cleaner than other fuels since it is mostly made of methane.

Application: When cofiring with natural gas, especially in companies with access to gas infrastructure, it can increase combustion efficiency, lower emissions, and offer operational flexibility.

Oil-Based Fuels:

Recycled oils are just one type of oil-based fuel that can be used to create alternative fuels.

Application: Cofiring with fuels obtained from oil can be utilized to diversify fuel sources in specific situations, albeit it is less common.

Plastics:

It is possible to process plastics to produce a fuel source for co-firing.

Application: Because of worries about emissions and the effects on the environment, cofiring with fuels obtained from plastic is contentious. On the other hand, certain systems might use produced plastics in a regulated co-firing process.

It's crucial to remember that technical viability, environmental impact, regulatory compliance, and economic considerations should all be taken into account when choosing fuels for cofiring. Sustainable cofiring techniques seek to maximize energy output while reducing negative effects on the environment and society.

2.5. Fuel Consideration

When considering fuels for co-firing applications, several factors need to be taken into account to ensure effective and sustainable combustion. These considerations encompass technical, economic, environmental, and regulatory aspects. Here are key factors to consider when selecting fuels for co-firing:

Calorific Value:

The calorific value of a fuel indicates its energy content per unit of mass. Higher calorific values contribute to better energy efficiency in combustion processes.

Moisture Content:

The moisture content of a fuel affects combustion efficiency. High moisture content can reduce the available energy and may lead to incomplete combustion.

Combustion Characteristics:

Different fuels have distinct combustion characteristics. Understanding factors such as ignition temperature, burnout rate, and flame stability is crucial for efficient co-firing.

Fuel Size and Form:

The size and form of the fuel particles influence combustion behavior. For example, fine powders may combust differently than larger solid pieces. Matching fuel size to combustion system requirements is essential.

Fuel Handling and Storage:

Considerations for the handling and storage of fuels include transportation logistics, storage facilities, and methods to prevent contamination. Proper handling reduces safety risks and ensures a consistent fuel supply.

Availability and Cost:

The availability and cost of fuels impact the economic feasibility of co-firing. Evaluating the cost-effectiveness of alternative fuels compared to traditional fuels is crucial for financial viability.

Environmental Impact:

Assess the environmental impact of fuels, including emissions during combustion and the overall life cycle of the fuel. Co-firing aims to reduce environmental impact, so choosing fuels with lower carbon content and fewer pollutants is desirable.

Waste Management:

If alternative fuels are waste-derived, consider the implications for waste management. Co-firing can provide an environmentally friendly solution for waste disposal, but it should be in compliance with waste regulations.

Regulatory Compliance:

Make sure the fuels you've chosen abide by all applicable local, state, and federal laws. There may be regional regulations pertaining to emissions, how trash is disposed of, and which fuels can be used.

Stability and Consistency:

Fuel stability and consistency are essential for the reliable operation of combustion systems. Inconsistent fuel quality can lead to operational challenges and impact product quality.

Safety Considerations:

Evaluate the safety aspects of handling and storing different fuels. Some fuels may pose safety risks due to their flammability, toxicity, or other characteristics.

Synergies with Existing Infrastructure:

Take into account how well the selected fuels work with the current combustion infrastructure. It might be necessary to adapt or modify current systems, and fuel compatibility with these changes is essential.

Public Perception:

Cofiring projects may be successful or unsuccessful depending on how the public views and accepts the selected fuels. It's critical to address issues with smell, aesthetic impact, and possible health and safety risks.

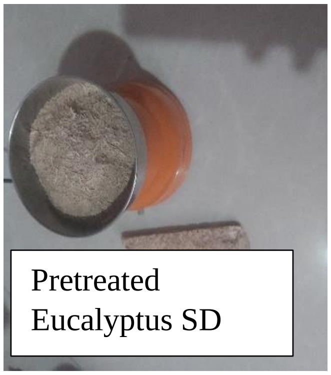
Choosing and using the right fuels for co-firing applications will be made easier with the aid of a thorough evaluation of these variables. Conducting comprehensive feasibility studies and fostering engagement with pertinent parties are crucial for ensuring the viability and sustainability of co-firing practices.

3. MATERIAL AND METHODS

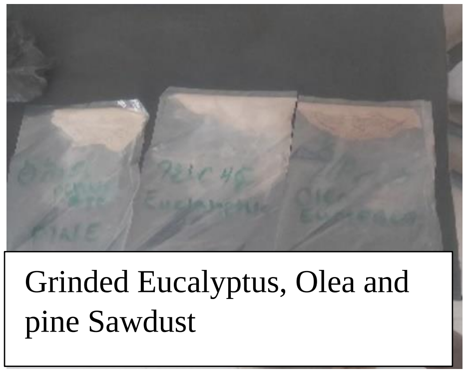
3.1. Materials

The materials used in this research included three biomass samples: Eucalyptus sawdust, Olea sawdust, and Pine sawdust along with various laboratory equipment essential for conducting the experiments. The complete list of materials and their specific functions in the laboratory is outlined as follows:

1. **Biomass Samples (Eucalyptus Sawdust, Olea Sawdust, and Pine Sawdust):** These samples were used as the primary experimental materials. One gram of each sample was prepared for analysis.
2. **Digital Analytical Balance:** This precision instrument was employed to accurately measure the mass of the biomass samples before experimentation.
3. **Furnace:** The furnace was utilized to heat the biomass samples under controlled conditions to assess their thermal properties.
4. **Desiccator:** Following the heating process, the samples were cooled and stored in a desiccator to prevent moisture absorption and ensure the accuracy of subsequent measurements.
5. **Crucibles:** These were used as containers to hold the biomass samples during the heating process, ensuring uniform thermal exposure.
6. **Notebook:** All observations, experimental data, and calculations were systematically recorded in a laboratory notebook for documentation and analysis.
7. **Grinding Mill and Grinding Disc:** These instruments were employed to grind the biomass samples into a fine powder, ensuring uniformity in particle size for accurate experimental results.



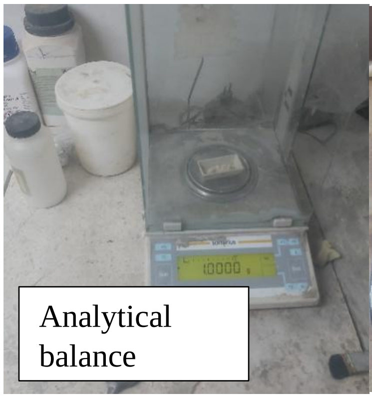
Pretreated Eucalyptus SD



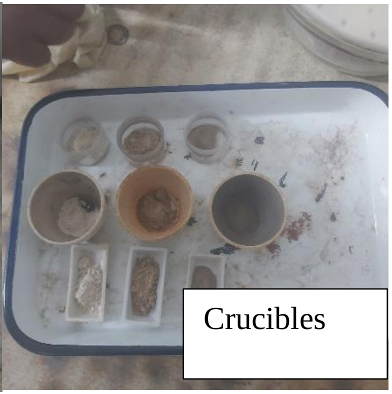
Grinded Eucalyptus, Olea and pine Sawdust

Rotatory grinding disc

Grinding mill



Analytical balance



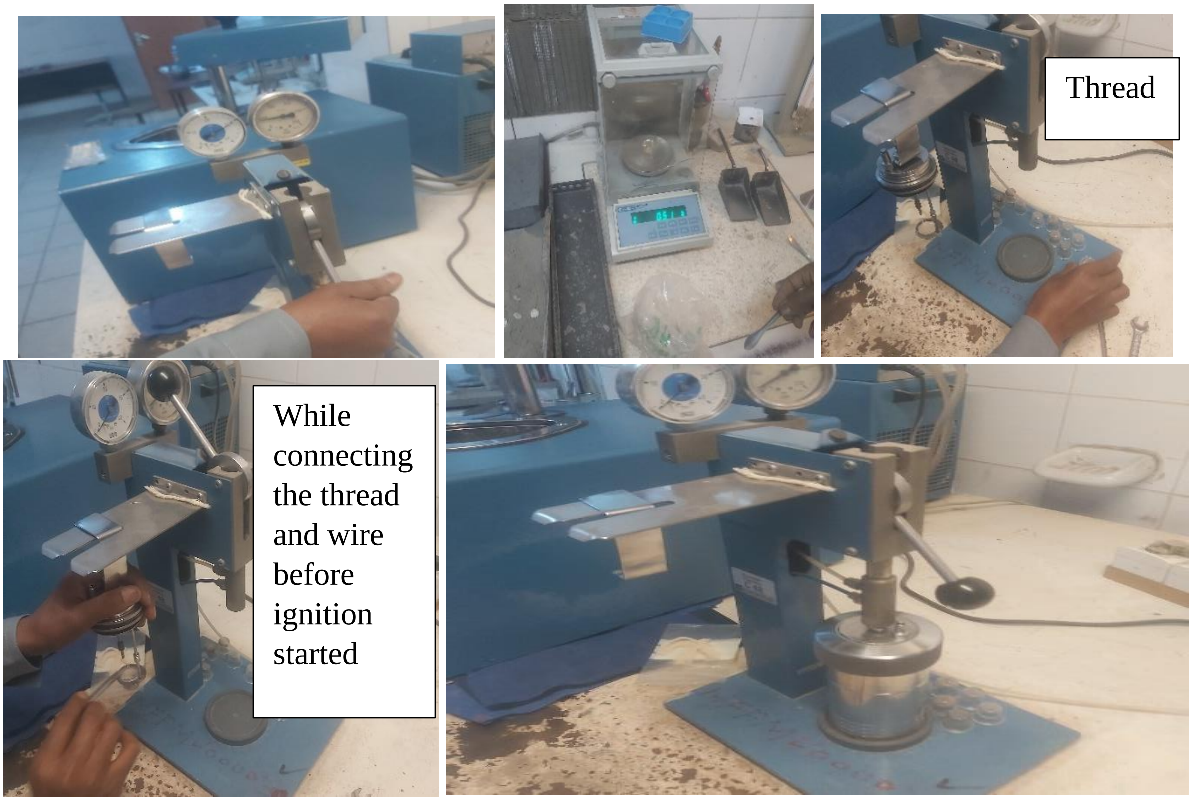
Crucibles

Desiccator

Furnace

Oven

Bomb calorimeter



Thread

While connecting the thread and wire before ignition started

Figure 4 list of materials used in lab

Calorific Value Determination Using Bomb Calorimeter

For the determination of CV using a bomb calorimeter, the following materials were used:

1. Eucalyptus, Olea, and pine sawdust: 0.5 grams of each sample were used.

2. Bomb calorimeter: Equipped with a bomb, ignition mechanism, water jacket, and thermometer.

3. Manganese ignition wire and thread: Used to ignite the sample inside the bomb.

4.Bomb calorimeter: to measure the energy content of each biomass.

3.2. Methods

3.2.1. Preparation of Biomass samples

The biomass samples used in this thesis were sourced and collected from designated locations to maintain consistency and relevance. Eucalyptus sawdust was sourced from Maichew Particle Board, while Pine sawdust and Olea sawdust were gathered from Aregawi Metal and Furniture Workshop situated in Midre Genet, Mekelle. Once collected, the samples underwent a drying process at room temperature for one week at home, following standard procedures, to decrease their moisture content and ensure uniformity in the analyses that followed. After drying, the samples were first ground using a coffee grinder at home to obtain a coarse powder. To achieve a finer consistency, a milling machine with a rotary milling disc was employed at the Messebo Cement Lab.

This phase was vital for converting the biomass into a fine powder, crucial for precise characterization and analysis. The samples that were finely ground were subsequently readied for proximate analysis and calorific value assessment, both of which took place at the Messebo Cement Factory Laboratory. These tests were performed following established ASTM methods, guaranteeing the dependability and consistency of the experimental findings.

3.2.2. Determination of proximate analysis

I. Moisture Content (MC) Determination

A precise measurement of one gram of the sieved Eucalyptus sample was taken and placed into previously weighed crucibles. These crucibles with the sample were then placed into a drying oven, where they were heated to a temperature of 105°C for one hour. This procedure was performed to ensure that all moisture was completely eliminated from the sample. Once the drying was complete, the crucibles were allowed to cool in a desiccator to avoid any moisture reabsorption from the air. The weight of the dried sample was noted after the crucibles had returned to room temperature.

The moisture content of the sample was subsequently calculated using the following equation:

$MC(\%) = \frac{(Ws+Wc)-Wc\ after}{Ws} * 100$--Eq 1

where:

- *Wc* represents the weight of the crucible,
- *Ws* represents the initial weight of the sample before drying,
- *W* dry represents the weight of the dried sample after the drying process.

This calculation yielded a quantitative assessment of the moisture level in the Eucalyptus sample, which is essential for comprehending the properties of the sample and guaranteeing the accuracy of further analyses. By employing controlled drying conditions and meticulous weighing techniques, the determination of moisture content was made reliable. The identical procedure was applied to the Olea and Pine sawdust samples to assess their moisture contents as well. This approach ensured methodological consistency across all biomass samples, facilitating a comparative evaluation of their moisture content and its effects on their overall characteristics..

II. Ash Content (AC) Determination:

A pre-weighed crucible was filled with one gram of the sieved Eucalyptus SD and placed in a furnace set to 550 °C, where it was allowed to burn entirely until a constant weight was achieved. After the burning process, the crucibles were meticulously removed and cooled in a desiccator. The weight loss was noted, and the ash content was determined using the given equation.

$AC(\%) = \frac{(Wa+wc)-Wc}{(Wc+Ws)before-WC} * 100$ ……………………………………Eq 2

Wa is weight of ash, Wc is weight of crucible and Ws is weight of sample

III. Volatile matter:

A precisely measured one gram of the sieved Eucalyptus sawdust (SD) sample was added to a crucible that had been previously weighed. After that, the sample-containing crucible was put in a furnace and heated to 550°C. To ensure that all biological stuff was entirely burned and that only the inorganic residue (ash) remained, the sample was left to burn until it reached a consistent weight. To avoid moisture absorption during cooling, the crucibles were carefully taken out of the furnace after combustion and allowed to cool in a desiccator. The following formula was used to determine the ash content once the weight loss was noted.:

$VM(\%) = \frac{(Wsample\ remained+Wc)-Wc\ after}{Wsample} * 100$……………………………………Eq 3

where:

- *Wa* represents the weight of the ash residue,
- *Wc* represents the weight of the crucible,
- *Ws* represents the initial weight of the sample before combustion,
- (*Wc*+*Ws*) before represents the combined weight of the crucible and sample before combustion.

To ensure consistency across all biomass samples in the study, the same methodology was then applied to the Olea and Pine sawdust samples to determine their respective ash contents. This equation gave a quantitative measure of the ash content in the Eucalyptus sawdust sample, which is a crucial parameter for evaluating the inorganic residue content and its implications for the sample's properties.

IV. Fixed carbon:

The percentage of fixed carbon (FC) in the biomass samples was determined indirectly by calculating the difference between 100% and the sum of the percentages of moisture content (MC), ash content (AC), and volatile matter (VM). This calculation was performed using the following equation:

Fixed Carbon (FC%) =100%−(MC%+AC%+VM%) …………Eq 4

where:

- FC% represents the percentage of fixed carbon,
- MC% represents the percentage of moisture content,
- AC% represents the percentage of ash content,
- VM% represents the percentage of volatile matter.

This approach provides a reliable and efficient way to estimate the fixed carbon content, which is a crucial parameter for understanding the energy potential and combustion characteristics of the biomass samples. The calculation was applied consistently across all samples, ensuring uniformity and comparability in the results. The fixed carbon content was derived by subtracting

the combined percentages of moisture content, ash content, and volatile matter from 100%. This method is based on the idea that the total composition of the biomass sample is accounted for by the sum of its moisture content, ash content, and fixed carbon.
Here are the results.

Characterization	Eucalyptus SD	Olea SD	Pine SD	South African Coal
CV in kcal/kg	4164	4358	4583	6224.6
Moisture content (MC) in %	2.80	2.35	2.38	0
Volatile matter (VM) in %	78.5	73	82.30	23.1
ASH content in %	1.63	1.95	0.43	22.93
Fixed Carbon (FC) in %	17.07	22.70	14.89	53.97
Sulfur(S) in %	0.0326	0.029	0.0086	0.769

Table 3 experimental result for the proximate analysis biomass samples

3.2.3. Determination of Ultimate Analysis

The amount of carbon, hydrogen, and nitrogen is measured using a CHN analyzer. Use an XRF spectrometer or elemental analyzer to find the sulfur content.
The final analysis result was produced using relations in equations and a correlation for determining elemental composition from proximate analysis of the test samples.

The analysis of variance (ANOVA) was carried out at 5 % significant level to determine whether there is a significant difference among the three biomass samples in terms of proximate analysis.

However, for this project, the ultimate analysis of biomass samples was done using correlational mathematical formulas by (due to the lack of the CHN analyzer and XRF spectrometer as follows). (Mahmut Daskin, 2024)

- $C = 0.637 * FC + 0.455 * VM$……………………….Eq 5
- $H = 0.052 * FC + 0.062 * VM$…………………….Eq 6
- $N = 0.01 * VM$…………………………………..Eq 7
- $S = 0.01 * Ash$…………………………………. Eq 8

Ultimate analysis in %	Eucalyptus SD	Olea SD	Pine SD
Hydrogen	5.75464	5.7064	5.87688
Carbon	46.59109	47.6849	46.93143
Nitrogen	0.785	0.73	0.823
Oxygen	46.83667	45.8497	46.36009

Sulphur	0.0326	0.029	0.0086

Table 4 Ultimate analysis results

The final examination of Eucalyptus sawdust (SD), Olea SD, and Pine SD provides important information regarding the elemental makeup of these biomass fuels, which is essential for assessing their appropriateness for co-firing in cement manufacturing. The examination shows that all three biomass samples have extremely low sulfur and nitrogen levels, which is a notable benefit. This trait suggests that their combustion will emit fewer pollutants, like sulfur oxides (SO_x) and nitrogen oxides (NO_x), compared to conventional coal. Consequently, these biomass fuels offer eco-friendly options for lowering emissions in industrial operations.

Among the three samples, Olea SD shows a marginally higher carbon content, indicating it may yield better combustion efficiency and greater energy output. This positions it as a strong option for situations where increasing energy production is critical. Conversely, Pine SD, which possesses a relatively higher hydrogen content, may provide enhanced flame stability during combustion, which is advantageous for ensuring steady and efficient burning conditions. Moreover, Pine SD's low sulfur content further increases its attractiveness as a cleaner fuel choice.

All three biomass fuels are marked by comparatively high oxygen content and low sulfur content, rendering them suitable for co-firing with coal in cement kilns. Their characteristics enable integration into current combustion systems without significantly altering operational conditions, thus allowing for a smoother shift to more sustainable fuel alternatives.

3.2.4 Computation based on the Literature Data

The ultimate and proximate analysis data for South African coal, used as a reference in this study, were obtained from established literature sources. This data served as a benchmark for comparing the properties of the biomass fuels (Eucalyptus SD, Olea SD, and Pine SD) with those of conventional coal, particularly in the context of co-firing in cement production. The inclusion of South African coal data allowed for a comprehensive evaluation of the potential advantages and limitations of substituting or supplementing coal with biomass fuels.

For data analysis and visualization, a detailed Microsoft Excel spreadsheet was done.. Excel's robust features and functions were utilized to organize, process, and analyze the experimental and literature-derived data. Key statistical and mathematical tools within Excel were applied to calculate parameters such as moisture content, ash content, volatile matter, fixed carbon, and elemental composition.

Then the characterization based on literature and numerical analysis using MS excel was given as shown below:

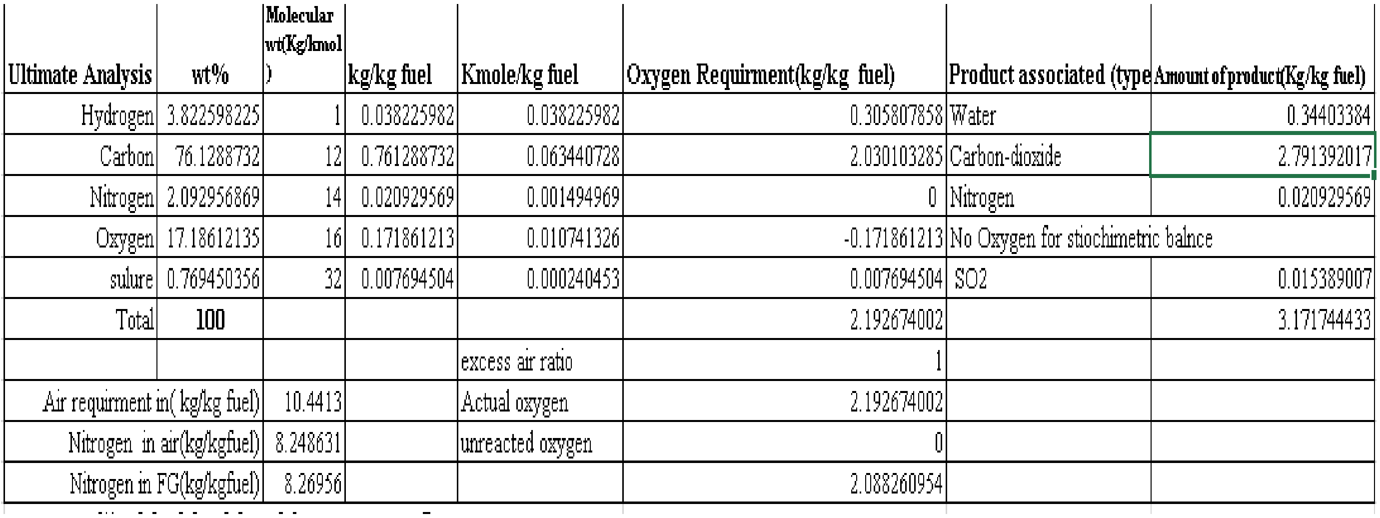
$LHV\ in \frac{MJ}{Kg} = HHV - \left(9 * \frac{H}{100} * 2.442\right) where\ 2.442\ is\ latent\ heat\ of\ vaporization\ of\ water$…Eq 9

Coal Analysis Type	**AC**	**VM**	**MC**	**FC**	**S**	**H**	**C**	**N**	**O**
Proximate	22.9%	23.1 %	0%	53.97 %	0.7694	-	-	-	-
Ultimate	-	-	-	-		3.82259	76.1288	2.0929	17.186
Parameter	HHV	LHV	A/F	EAR	O req	FT	CO2	SO2	NOX
Value	25.195	26.04	10.4413	2.08826	2.19267	1794.07	279.139	1.5389	1.5389
Remark	literature	Calculated using excel							

Ultimate Analysis	**wt%**	**Molecular wt(Kg/kmol)**	**kg/kg fuel**	**Kmole/kg fuel**	**Oxygen Requirement (kg/kg fuel)**	**Product associated (type)**	**Amount of product (Kg/kg fuel)**
Hydrogen	3.82259822	1	0.0382	0.0382	0.30580785	Water	0.344
Carbon	76.1288732	12	0.7612	0.0634	2.03010328	Carbon-dioxide	2.791392017
Nitrogen	2.09295686	14	0.0209	0.0014	0	Nitrogen	0.020929569
Oxygen	17.1861213	16	0.171861213	0.010741326	-0.17186121	No Oxygen for stoichiometric balance	
sulfur	0.76945035	32	0.007694504	0.000240453	0.007694504	SO2	0.015389007

Total	**100**				2.19267400		3.171744433
				excess air ratio	1		
	Air requirement in(kg/kg fuel)	10.44		Actual oxygen	2.19267		
	Nitrogen in air(kg/kg fuel)	8.248		unreacted oxygen	0		
	Nitrogen in FG(kg/kg fuel)	8.269			2.08826		

Table 5 Ultimate and proximate **analysis of the coal based on excel calculation**



Ultimate Analysis	wt%	Molecular wt(Kg/kmol)	kg/kg fuel	Kmole/kg fuel	Oxygen Requirment(kg/kg fuel)	Product associated (type	Amount of product(Kg/kg fuel)
Hydrogen	3.822598225	1	0.038225982	0.038225982	0.305807858	Water	0.34403384
Carbon	76.1288732	12	0.761288732	0.063440728	2.030103285	Carbon-dioxide	2.791392017
Nitrogen	2.092956869	14	0.020929569	0.001494969	0	Nitrogen	0.020929569
Oxygen	17.18612135	16	0.171861213	0.010741326	-0.171861213	No Oxygen for stiochimetric balnce	
sulure	0.769450356	32	0.007694504	0.000240453	0.007694504	SO2	0.015389007
Total	100				2.192674002		3.171744433
				excess air ratio	1		
Air requirment in(kg/kg fuel)	10.4413			Actual oxygen	2.192674002		
Nitrogen in air(kg/kgfuel)	8.248631			unreacted oxygen	0		
Nitrogen in FG(kg/kgfuel)	8.26956				2.088260954		

Figure 5 Ultimate and proximate **analysis of the coal based on excel calculation**

3.2.5. Calorific value determination

The Higher Heating Value (HHV), often known as the calorific value, of the three types of biomass fuels (Eucalyptus SD, Olea SD, and Pine SD) was assessed according to ASTM standards using a bomb calorimeter. The HHV indicates the total amount of energy released when a defined quantity of the fuel is entirely burned. The bomb calorimeter setup included several essential components, such as a crucible for holding the sample, a stainless-steel bomb, pure oxygen, a manganese ignition wire, thread, water, a stirrer, a thermometer, and an ignition circuit linked to the bomb.

Before the experiment, the three biomass samples were finely ground using a grinding mill and then sieved to ensure consistency. About 0. 5 grams of each powdered sample was meticulously weighed and placed into the crucible of the calorimeter. The bomb was subsequently pressurized with pure oxygen at around 30 atmospheres (ATM), and a small quantity of water was added to saturate the internal environment, ensuring complete combustion. The bomb was then immersed in a water jacket, and the sample was electrically ignited via the ignition circuit.

During the combustion process, energy was emitted in the form of heat, which transferred through the stainless-steel walls of the bomb, elevating the temperature of the bomb, its contents, and the adjacent water jacket. Temperature readings were taken before, during, and after combustion to calculate the heat produced. Appropriate adjustments were made to accommodate heat contributions from other processes, as well as thermometer and thermochemical corrections. The HHV was computed manually based on these temperature readings along with the specific heat capacity of the system.

The process was repeated for the other two biomass samples, Olea SD and Pine SD, to ascertain their individual HHVs. Ultimately, the calorific value for each sample was derived using the gathered data, which included the initial and final temperatures of the water jacket, and correction factors were applied for heat loss or other variables as indicated by the calorimeter manufacturer.

The formula used for calculating the HHV is as follows:

$$CV(HHV) = (\Delta T * C - \frac{Qr}{m}) * F\ ,\ \Delta T = Tf - Ti, C = 2183\frac{cal}{c}, Qr = 19.1\frac{cal}{c}, m = 0.5\ g, F = correction\ factor \text{ ………………………………………………………..Eq 10}$$

The results are presented in the table below.

Fuel type	HHV in Kcal/kg	In MJ/Kg	Remark
Eucalyptus SD	4164 kcal/kg	17.43	Experimentally determined
Olea SD	4358	18.23	
Pine SD	4583	19.18	
South African Coal	6224.6	26.04	From Literature

Table 6 Higher Heating Value (HHV)

Analysis Of Eucalyptus, Olea and Pine sawdust

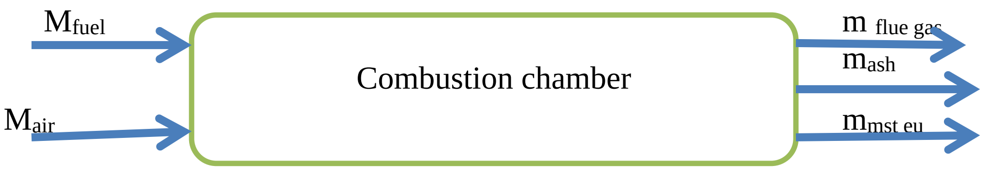


Figure 6 mass balance in the combustion chamber

The obtainable combustion temperature (TF), commonly known as the flame temperature, of the biomass fuels was established by executing an energy balance over the kiln control volume under steady-state adiabatic conditions. This computation assumes the absence of heat loss to the environment (adiabatic conditions) and that the system functions at a steady state, indicating that all energy inputs and outputs are equivalent. To aid in this intricate calculation, an Excel Solver tool was utilized, which enabled the iterative solving of the energy balance equations.

The energy balance was established by considering the enthalpy of the reactants (biomass fuel and air) and the enthalpy of the combustion products (flue gases, water vapor, and other by-products).

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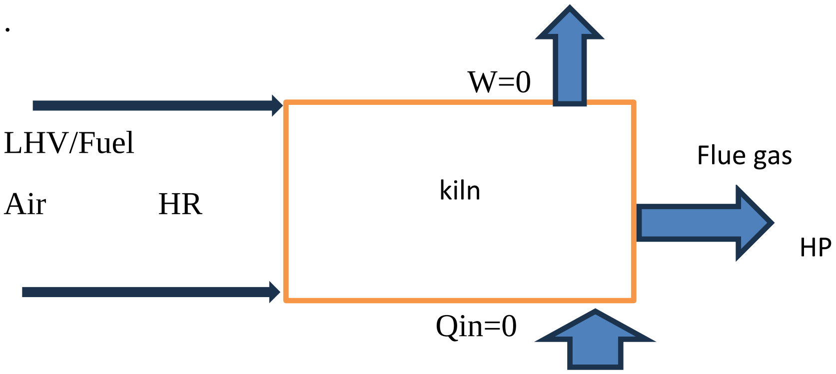

Figure 7 Energy balance in the Kiln

The key steps involved in the calculation are as follows:

The flame temperature (TF) is determined by doing energy balance on the furnace, hence

Energy in = Energy out

$LHV + HR + Qin = HP + W$, It is assumed that combustion takes place under adiabatic conditions, i.e. no heat transfer is permitted across the boundary of the system so that

Qin (heat transferred to the system) and work done by the system(W) are equal to Zero

Hence, $LHV + HR = HP$

Where, LHV is lower heating value of eucalyptus and from the experiment in Messobo, the LHV was found to be 16160 KJ/Kg using equation .where,

H_R = heat of reactant (Nitrogen and oxygen)

$H_{p=}$ heat of the products.

H_R(heat of the reactants) is for both oxygen and Nitrogen found in the air and they are determined as follows:

$\mathrm{HR} = (ti - 298)\boldsymbol{\Sigma}(mcp)$

$HR = HR,N2 + HR,O2$

$H_{R,\ O2}$ is the heat of reactant of oxygen and it is calculated as;

$\mathrm{HR,\ O_2= MO_2*\Delta T*Cp=MO_2*(Ti\text{-}298)*Cp}$

$\mathrm{HR,\ N_2= MN_2*\Delta T*Cp=NO_2*(Ti\text{-}298)*Cp}$

Where MO_2 = mass of oxygen (Kg) in air, MN_2= mass nitrogen (Kg) in air.

Ti = is the initial temperature in K where the air and fuel is supplied and 298 is the reference temperature.

Cp= specific heat capacity of oxygen and nitrogen respectively at constant pressure in KJ/Kg.k and it is determined as function of temperature.

That is $Cp = F(T)$,the specific heats of the oxygen and nitrogen can be evaluated at the mean temperature (T),

that is $T = \frac{(ti + 298)}{2}$

A polynomial expression is commonly used to evaluate the specific heat capacity (*Cp*) of both the reactants and the products involved in combustion processes. This approach is particularly useful because *Cp* varies with temperature, and a polynomial function can accurately capture this dependence. The general form of the polynomial expression is as follows:

$$CP = a[0] + a[1]T + a[2]T2 + a[3]T3 \ldots\ldots\ldots\ldots\ldots an(n)Tn$$

Values of the coefficients in this polynomial expression for some gases were taken from literature as shown in the table below.

Gases	**a[0]**	**a[1]**	**a[2]**	**a[3]**	**a[4]**	**a[5]**
Carbon dioxide	0.818205	0.00099739	$-7.6E^{-07}$	$2.79744E^{-10}$	$-3.8726E^{-14}$	0.00E+00
Carbon monoxide	1.03	0.0001274	$2.41E^{-07}$	$-2.174E^{-10}$	0.4956	0.00E+00
Water (vapor)	1.86024	0.0003232	$5.85E^{-07}$	$-3.5846E^{-10}$	$5.93307E^{-14}$	0.00E+00
Oxygen	0.9057	0.0002941	$9.65E^{-08}$	$-3.364E^{-10}$	$2.021E^{-13}$	$-3.811E^{-17}$
Nitrogen	1.30709	$8.119E^{-06}$	$4.86E^{-07}$	$-4.6162E^{-10}$	$1.6814E^{-13}$	$-2.18231E^{-17}$
Hydrogen	14.35	0.0009947	$-2.5E^{-06}$	0.4978	$-2.856E^{-12}$	0.5275

Sulphur dioxide	0.818205	0.0009974	-7.6E^{-07}	2.79744E^{-10}	-3.8726E^{-14}	0.00E+00

Table 7 Polynomial Coefficients for specific heats of gasses

Hence, the $C_{p,O2}$ value for oxygen can be determined using the coefficients from the table above and the initial temperature(Ti) where the air is supplied is 298K ,thus the mean temperature (T) can be calculated as:

$T = \frac{(ti + 298)}{2}$. Therefore, $HR = (ti - 298)\boldsymbol{\Sigma}(mcp) = HR, N2\ +\ HR, O2$

$$HR\ =\ (ti - 298) * \{(M_{o2} * CP, o2)\ + (* M_{N2} * CP, N2)\}$$

Mass of oxygen (MO_2) and mass of nitrogen (MN_2) in the air is determined as follows:

Let us determine the actual mass of oxygen required for the combustion of 1 Kg of biomass waste (white Eucalyptus) using the ultimate analysis results or composition of the biomass waste.

$C + O2 \longrightarrow CO2$

12 Kg C + 32Kg O2 $\longrightarrow$ 44Kg CO2, the mass of ‘C’ from the ultimate analysis result is, 46.59%

The actual oxygen required $= 32 * \frac{0.4659}{12} = 1.2424Kg\frac{O2}{Kg}\ eucalyptus$

$2H_2 + O2 \longrightarrow 2H_2O$

4Kg H_2 +32Kg O_2 $\longrightarrow$ 36Kg of H_2O, the mass of ‘H_2’ from the ultimate analysis result is, 5.754%.

The actual oxygen required$= 32 * \frac{0.05754}{4} = 0.4603Kg\ O2/Kg\ eucalyptus$

Composition	Mass fraction	Oxygen required (Kg/Kg Eucalyptus)
Carbon(C)	0.4659	1.2424
Hydrogen(H2)	0.057	0.4603
Nitrogen(N2)	0.0078	-
Oxygen(O2)	0.4683	-0.4683
Sulphur	0.000326	**0.000326**

Total Oxygen required		**1.2426**

Table 8 Oxygen required per Kg of eucalyptus SD

The total amount of oxygen required for the combustion of one kg of Eucalyptus SD with no excess air is **1.2426.** Which is total mass of oxygen required,$MO2 = 1.2426 Kg/Kg\ eucalyptus$

Hence, mass of total air required to burn one Kg of biomass waste will be $m.air = mo2/0.21$, ,where air is assumed to contain 21% O2 by mass:

$m.air = 1.2424/0.21$,so $m.air = 5.917 Kg/kg\ of\ eucalyptus$

Moreover, we can determine the mass of nitrogen (N2) in the air as follows:

$mN2 = m.air * 0.79$, where air is assumed to contain 79% O_2 by mass $m.N2 = 5.917 * 0.79$

$m.N2 = 4.674 Kg/Kg\ Eucalyptus$

Therefore, the stoichiometric air fuel ratio would be 5.917**:1**

A 20% excess air was assumed ,so, the actual air/ fuel would be =5.917 +20%* 5.917=7.1

The Cp value for both oxygen and nitrogen using the above polynomial expression can be determined using solver Excel tool for accuracy as it is bulky to determine it manually.

$HR = HR,O2 + HR,N2$

HR = (Ti-298) *{(MO2*Cp, O2) +(*MN2*Cp, N2)}

By substituting the 'Cp' for both nitrogen and oxygen,' Ti' as well as mass of oxygen (MO2) and mass of nitrogen in the air (MN2), the heat of the reaction (HR) will be determined using an excel tool easily.

The heat of the products, HP (KJ/K.g) is determined same procedure as the above (HR).

From the ultimate analysis result, the composition of the eucalyptus SD is 46.83 O2, 5.754% H2, 46.59%C and 0.785% N2.

$HP = (Tf - 298)\boldsymbol{\Sigma}(mcp)p$ Where, Tf, is the flame temperature or achievable combustion temperature's' and 'M' are the specific heat capacity and mass of the product gases respectively.

This relationship cannot be solved unambiguously for" Tf" as there will be a considerable difference between Tf and the reference temperature 298. Therefore, first the specific heat of the products combustion has to be evaluated so as to find the flame temperature (T_f).

First the mass of the product gases have to be determined from the combustion reaction using the stoichiometric equation.

$C + O_2 \longrightarrow CO_2$, from the ultimate analysis result mass of C is 46.59% or 0.4659, then

12 kg of C $\longrightarrow$ 44 Kg of CO2

0.4659 Kg of C ?

Therefore, mass of CO2 will be $= \frac{44\ \text{Kg}\ *0.4659\ \text{Kg}}{12\ kg}$ = 1.7083 Kg of CO2

$2H_2 + O2 \longrightarrow 2H_2O$ and the percentage of H_2 in the biomass composition is 5.754%(0.05754) Kg.

4(1) Kg of H2 $\longrightarrow$ 2(18) Kg of H2O

0.0575Kg of H2 ?

Then, the, mass of water in the product reaction is $= \frac{2*18*0.05754}{4*1}$=0. 517 Kg of water

The mass of nitrogen (N2) in in the product reaction is 0.00785 Kg as it is 0.785% in the eucalyptus SD composition, that is mass in mass out (N2 is an inert as a result it does not make reaction).

Therefore, the total mass of the product gases (flue gases) of the biomass waste is the sum of the water produced ,carbon dioxide and Nitrogen and the mass of N2 in the Air

Mass of Flue gases = 0.517+ 0.00785 +1.7083 +4.674 =6.907 **Kg/kg of fuel**

Using the above polynomial coefficient table of the specific heat of gases, the' CP' value of the flue gases can be determined likewise.

CP,$_{CO2}$ $= a[0] + a[1]T + a[2]T2 + a[3]T3 \ldots\ldots\ldots\ldots\ldots an(n)Tn$, the temperature T is here the average of flame temperature and reference temperature,298K

That is, $\mathbf{T}=\frac{\boldsymbol{Tf+298}}{\mathbf{2}}$

CP,$_{H2o}$ $= a[0] + a[1]T + a[2]T2 + a[3]T3 \ldots\ldots\ldots\ldots\ldots an(n)Tn$ and

CP,$_{N2}$ $= a[0] + a[1]T + a[2]T2 + a[3]T3 \ldots\ldots\ldots\ldots\ldots an(n)Tn$

Then, $HP = (Tf - 298)\boldsymbol{\Sigma}(mcp)p$

Alternatively, the above equation was rewritten by substituting their corresponding specific heat capacity (Cp) and mass of the product gases (M).

$$HP = (Tf - 298) * \{(MCo2 * cpCO2) + (MH2O * cpH2O) + (MN2 * CpN2)\}$$

Let us substitute HP and HR to the general equation : $LHV + HR = HP$

$LHV + (ti - 298) * \{(Mo2 * CP,o2) + (* MN2 * CP,N2)\} = (Tf - 298) * \{(Mco2 * cpco2) + (MH2o * cpH2o) + (MN2 * CpN2)\}$…………..Eq 11

By inserting all the pertinent values into the energy balance equations and using an Excel Solver tool, the possible flame temperature (Tf) for the burning of Eucalyptus sawdust (SD) was found to be 1832 K (1559°C). This assessment was predicated on the following essential assumptions, which were crucial for simplifying the evaluation and attaining precise outcomes:

1. Minimal SO_2 Contribution: The presence of SO_2 in the combustion byproducts was disregarded since the level of sulfur in the biomass fuels is very low, leading to a negligible quantity of SO_2 moles. This presumption is justified considering the limited sulfur content in the biomass samples.

2. Total Combustion: It was believed that the combustion operation is complete, signifying that no carbon monoxide (CO) is generated due to incomplete combustion. This indicates that all carbon within the fuel converts to CO_2, and all hydrogen transforms into H_2O.

3. Ideal Air-Fuel Ratio: The assessment relied on the theoretical (stoichiometric) air-fuel ratio, which indicates the least amount of air necessary for total combustion. This precept guarantees that the flame temperature determination is grounded on perfect conditions without exceeding air.

4. Insulated Conditions: The scenario was presumed to be adiabatic, indicating there is no heat dissipation to the environment, and the combustion byproducts do not do any work on the environment. This streamlines the energy balance by concentrating exclusively on the heat produced by the combustion event.

Achievable Flame Temperature for Eucalyptus SD:

The flame temperature for Eucalyptus SD was determined to be 1832 K (1559°C) based on the previously mentioned assumptions. This figure indicates the highest possible temperature under optimal adiabatic conditions.

By using the same methods and assumptions described for calculating the flame temperature (Tf) of Eucalyptus sawdust (SD), the flame temperatures for the other biomass samples Olea SD and Pine SD were similarly established. The approach included conducting an energy balance under steady-state adiabatic conditions, utilizing the Excel Solver tool to iteratively determine Tf, and applying identical assumptions to maintain consistency and precision.

The final results for the flame temperatures of the three biomass samples are as follows:

Fuel type Flame Temperature	10% Cofiring ratio	15% Cofiring ratio	20% Cofiring ratio	Remark
Eucalyptus SD	1770.775551	1797.841442	1825.954982	

Olea SD	1801.819626	1775.726893	1828.882036	
Pine SD	1784.065516	1810.563785	1838.056242	

Table 9 Flame temperature

4. RESULT AND DISCUSSION

4.1. Result

Fuel blend composition based on mass

The fuel blend composition was calculated using the mass fraction of the fuel blend, which combines biomass and coal in specific proportions. The composition of each species in the fuel blend was determined using the following equation:

$X = Mbiomass \times Xbiomass + Mcoal \times Xcoal$……………………………………. Eq 12

where:

- X represents the number of moles of a specific species (e.g., carbon, hydrogen, oxygen) in the fuel blend,
- Mcoal is the mass fraction or percentage of coal in the fuel blend,
- Xcoal is the number of moles of the species in coal,
- Mbiomass is the mass fraction or percentage of biomass in the fuel blend,
- Xbiomass is the number of moles of the species in biomass.

Steps for Calculating Fuel Blend Composition:

1. Determine Mass Fractions:
    - Define the mass fractions of coal (Mcoal) and biomass (Mbiomass) in the fuel blend.
2. Obtain Molar Composition:
    - Use the ultimate analysis data to determine the number of moles of each species (e.g., carbon, hydrogen, oxygen, nitrogen, sulfur) in both coal and biomass.
3. Apply Equation 12:
    - For each species, calculate its contribution to the fuel blend using Equation 12. Multiply the mass fraction of coal by the number of moles of the species in coal, and add it to the product of the mass fraction of biomass and the number of moles of the species in biomass.
4. Sum the Contributions:
    - Repeat the calculation for all species to determine the total molar composition of the fuel blend.

Based on equation 12 above the following results were calculated using excel tool:

Characterization	10% cofiring	15% cofiring	20% Cofiring

CV in kcal/kg	6018.576	5915.544	5812.512
MC in %	0.28	0.42	0.56
VM in %	28.64	31.41	34.18
ASH in %	20.8	19.735	18.67
FC in %	50.28	48.435	46.59
Sulfur %	0	0	0

Table 10 Proximate analysis and CV values of Eucalyptus Cofiring ratio

Ultimate analysis in %	10%	15%	20%
Hydrogen	4.015802402	4.112404	4.209007
Carbon	73.17509488	71.69821	70.22132
Nitrogen	1.962161182	1.896763	1.831365
Oxygen	20.15117621	21.6337	23.11623
Sulphur	0.69576532	0.658923	0.62208

Table 11 Ultimate analysis eucalyptus SD at Cofiring ratio

Analysis of Coal	**AC**	**VM**	**MC**	**FC**	**S**	**H**	**C**	**N**	**O**
Proximate	22.9%	23.1 %	0%	53.97 %	0.7694	-	-	-	-
Ultimate	-	-	-	-		3.82259	76.1288	2.0929	17.186
Parameter	HHV	LHV	A/F	EAR	O req	FT	CO2	SO2	NOX
value	25.195	26.04	10.4413	2.08826	2.19267	1794.07	279.139	1.5389	1.5389
Remark	literature	Calculated using excel							

Table 12 Coal proximate and ultimate analysis

4.1.1 Environmental analysis

Analysis of CO_2 Emission

The assessment of CO_2 emissions stemming from cement manufacturing at Messebo Cement Factory, taking into account co-firing with biomass fuels (Eucalyptus SD, Olea SD, and Pine SD) in conjunction with coal, requires a thorough examination of the carbon content of the fuels, the clinker factor, and the thermal energy needed for clinker production. Presented below is a sequential breakdown of the calculations, using Eucalyptus as a case study, along with a comparison of CO_2 emissions for the various fuels.

Eucalyptus SD

Parameters and Assumptions:

1. Carbon Content of Fuels:
    - Eucalyptus SD: 46.59%
    - Olea SD: 47.68%
    - Pine SD: 46.93%
    - Coal: 76.2%
2. Clinker Factor: 0.8 (80% of cement is clinker).
3. Heat Consumption for Clinker Formation: 3300 kJ/kg of clinker.
4. Lower Heating Value (LHV) of 10% Eucalyptus Blend: 23839.75 kJ/kg.
5. CO_2 Emission Calculation:
    - The stoichiometric relationship between carbon (C) and CO_2 is:

      $$C+O2\rightarrow CO2C+O2\rightarrow CO2$$

        - Molar mass of C = 12 g/mol
        - Molar mass of CO_2 = 44 g/mol
    - Therefore, 1 kg of carbon produces 44/12 =3.6667kg of CO2.

Calculation for 10% Eucalyptus Co-Firing:

Step 1: Carbon Content in 1 kg of Eucalyptus Blend

- The carbon content in 1 kg of the blend is:

Carbon=0.73175

Step 2: CO_2 Emitted from 1 kg of 10% Eucalyptus Blend

- Using the stoichiometric relationship:

CO2 emitted=0.73175×44/12=2.683 kg of CO2 per 1 kg of fuel

Step 3: Clinker Produced from 1 kg of 10% Eucalyptus Blend

- The LHV of the blend is 23839.75 kJ/kg.
- Heat required to produce 1 kg of clinker = 3300 kJ.
- Clinker produced from 1 kg of fuel:

Clinker=23839.75/3300=7.224 kg of clinker per 1 kg of fuel

Step 4: Cement Produced from 1 kg of 10% Eucalyptus Blend

- Clinker factor = 0.8 (80% of cement is clinker).

  Cement produced:

Cement=7.224×0.8=5.779 kg of cement per 1 kg of fuel

Step 5: CO_2 Emitted per 1 kg of Cement

- CO_2 emitted per 1 kg of cement:

CO2 per kg of cement=2.683/5.779=0.46426 kg of CO2 per kg of cement

Comparison of CO_2 Emissions for Different Fuels

The same procedure was applied to calculate CO_2 emissions for the other fuels (Olea SD, Pine SD, and Coal). The results are summarized below:

Fuel Type	Carbon Content (%)	CO_2 Emitted per 1 kg of Fuel (kg)	Cement Produced per 1 kg of Fuel (kg)	CO_2 Emitted per 1 kg of Cement (kg)
Eucalyptus SD	46.59	2.683	5.779	0.46426
Olea SD	47.68	2.748	5.779	0.475
Pine SD	46.93	2.704	5.779	0.468
Coal	76.2	4.394	5.779	0.760

Table 13 CO_2 emissions per kg/cement

1. Biomass Fuels Reduce CO_2 Emissions:
   - Co-firing with biomass (Eucalyptus, Olea, or Pine) significantly reduces CO_2 emissions compared to using coal alone.
   - For example, 10% Eucalyptus co-firing emits 0.46426 kg of CO_2 per kg of cement, whereas coal emits 0.760 kg of CO_2 per kg of cement.
2. Olea SD Slightly Higher Emissions:
   - Olea SD has a slightly higher carbon content (47.68%) compared to Eucalyptus and Pine, resulting in marginally higher CO_2 emissions.
3. Pine SD as a Balanced Option:

  - Pine SD offers a balance between carbon content and CO_2 emissions, making it a viable option for cleaner combustion.
4. Coal as the Highest Emitter:
  - Coal, with its high carbon content (76.2%), produces the highest amount of CO_2 per kg of cement.

The computations indicate that the co-firing of biomass fuels alongside coal in cement manufacturing can greatly lower CO_2 emissions. Eucalyptus SD, Olea SD, and Pine SD provide significant environmental advantages in comparison to coal, with Eucalyptus SD proving to be the most efficient in emission reduction. These results emphasize the potential role of biomass fuels as sustainable options for minimizing the carbon footprint in the cement production process at Messebo Cement Factory.

Coal

The assessment of CO_2 emissions from the burning of coal in cement manufacturing employs a methodology akin to that applied to biomass fuels. Below is a comprehensive breakdown of the calculations pertaining to coal, which includes the quantity of CO_2 produced per kilogram of coal and the related cement production..

Parameters for Coal:

1. Carbon Content of Coal: 76.2% (0.761 kg of carbon per 1 kg of coal).
2. Lower Heating Value (LHV) of Coal: 25195 kJ/kg.
3. Heat Consumption for Clinker Formation: 3300 kJ/kg of clinker.
4. Clinker Factor: 0.8 (80% of cement is clinker).

Step-by-Step Calculation for Coal:

Step 1: CO_2 Emitted from 1 kg of Coal

- The stoichiometric relationship between carbon (C) and CO_2 is:

$$C+O2\rightarrow CO2$$

  - Molar mass of C = 12 g/mol
  - Molar mass of CO_2 = 44 g/mol
- Therefore, 1 kg of carbon produces 44/12=3.6667 kg of CO
- For 1 kg of coal:

CO2 emitted=0.761×44/12=2.785 kg of CO2 per 1 kg of coal

Step 2: Clinker Produced from 1 kg of Coal

- The LHV of coal is 25195 kJ/kg.
- Heat required to produce 1 kg of clinker = 3300 kJ.
- Clinker produced from 1 kg of coal:

Clinker=25195/3300=7.634 kg of clinker per 1 kg of coal

Step 3: Cement Produced from 1 kg of Coal

- Clinker factor = 0.8 (80% of cement is clinker).
- Cement produced: Cement=7.634×0.8=6.107 kg of cement per 1 kg of coal

Step 4: CO_2 Emitted per 1 kg of Cement

CO2 per kg of cement=2.785/6.107=0.456 kg of CO2 per kg of cement

Summary of Results for Coal:

Parameter	Value
CO_2 emitted per 1 kg of coal	2.785 kg of CO_2
Clinker produced per 1 kg of coal	7.634 kg of clinker
Cement produced per 1 kg of coal	6.107 kg of cement

Parameter	Value
CO_2 emitted per 1 kg of cement	0.457015 kg of CO_2

Table 14 CO2 per kg coal

The table below compares CO_2 emissions for coal and biomass fuels (Eucalyptus SD, Olea SD, and Pine SD):

Fuel Type	CO_2 Emitted per 1 kg of Cement (kg)
Coal	0.4577
Eucalyptus SD	0.46426
Olea SD	0.475
Pine SD	0.468

Table 15 emission comparison

The computations illustrate that biomass fuels provide a more sustainable and eco-friendly option. Co-firing biomass alongside coal can assist in lowering the carbon footprint of cement manufacturing, which is in line with international initiatives aimed at addressing climate change.

Below is the finished Table, which presents the comparison of CO_2 emissions when utilizing coal compared to co-fired Eucalyptus sawdust (SD). The table encompasses the quantity of CO_2 released per 1 kg, 100 kg, and daily cement production, in addition to the variance in CO_2 emissions between the two types of fuel.

Amount of Cement Produced	CO_2 Emitted from Coal (kg)	CO_2 Emitted from Co-Fired Eucalyptus (kg)	Difference in CO_2 Emitted (kg)
Per 1 kg	0.457015	0.455622	0.001393
Per 100 kg	45.7015	45.56216	0.13934
Per Day	45701.5	45562.16	139.34

Table 16 Carbon Dioxide Emissions of Coal and Co-Fired Eucalyptus

1. Per 1 kg of Cement:
    - Coal emits 0.457015 kg of CO_2.

    - Co-fired Eucalyptus emits 0.455622 kg of CO_2.
    - The difference in CO_2 emissions is 0.001393 kg, favoring co-fired Eucalyptus.
2. Per 100 kg of Cement:
    - Coal emits 45.7015 kg of CO_2.
    - Co-fired Eucalyptus emits 45.56216 kg of CO_2.
    - The difference in CO_2 emissions is 0.13934 kg, favoring co-fired Eucalyptus.
3. Per Day of Cement Production:
    - Assuming daily cement production of 100,000 kg (100 metric tons):
        - Coal emits 45,701.5 kg of CO_2.
        - Co-fired Eucalyptus emits 45,562.16 kg of CO_2.
        - The difference in CO_2 emissions is 139.34 kg, favoring co-fired Eucalyptus.

This is small but Significant Difference:

- While the difference in CO_2 emissions per kg of cement is small (0.001393 kg), it becomes more significant when scaled up to larger quantities (e.g., 139.34 kg per day).
- Over time, this reduction in CO_2 emissions can contribute to a lower carbon footprint for the cement production process.

Environmental Benefits of Co-Firing

The calculations indicate that biomass fuels provide a more sustainable and eco-friendly option. Blending biomass with coal can contribute to lowering the carbon footprint in cement manufacturing, which aligns with worldwide initiatives to address climate change.

Below is the finished Table, illustrating the comparison of CO_2 emissions when utilizing coal compared to co-fired Eucalyptus sawdust (SD). The table presents the quantity of CO_2 released per 1 kg, 100 kg, and daily cement production, along with the variation in CO_2 emissions between the two fuels.

This highlights the potential of biomass co-firing as a sustainable strategy for reducing the environmental impact of cement production.

The percentage reduction in CO_2 emissions achieved by co-firing biomass fuels (Eucalyptus SD, Olea SD, and Pine SD) with coal in the cement kiln process is calculated using the formula:

$$\% \text{ Reduction} = \text{Difference in CO2 Emissions}/\text{Initial CO2 Emissions} \times 100$$

The results for different co-firing percentages (10%, 15%, and 20%) are summarized in the table below. These values demonstrate the environmental benefits of replacing a portion of coal with biomass fuels.

Co-Firing Percentage	**Eucalyptus SD (%)**	**Olea SD (%)**	**Pine SD (%)**
10%	0.304875	0.487676	0.487676
15%	0.465978	0.744069	0.744069
20%	0.633305	1.009417	1.009417

Table 17 Percentage Reduction in CO_2 Emissions

Increasing Co-Firing Percentage:

As the biomass co-firing percentage rises, the decline in CO_2 emissions also escalates. For instance, at 20% co-firing, all three biomass fuels achieve more than a 1% reduction in CO_2 emissions.

Olea SD and Pine SD:

Olea SD and Pine SD demonstrate the same reductions in CO_2 emissions across all co-firing percentages. This is likely attributable to their comparable carbon content and combustion properties.

Eucalyptus SD:

Eucalyptus SD exhibits marginally lower reductions in CO_2 emissions than Olea SD and Pine SD. This is due to Eucalyptus SD having a slightly diminished carbon content.

Environmental Impact:

Even minor decreases in CO_2 emissions (e. g. , 0. 304875% at 10% co-firing) can result in a significant cumulative effect over time, particularly in extensive industrial processes like cement manufacturing.

Co-firing biomass fuels lowers greenhouse gas (GHG) emissions and supports a cleaner environment.

The table illustrates that co-firing biomass fuels with coal in cement production can lead to substantial reductions in CO_2 emissions. The percentage reduction grows with increased co-firing percentages, with Olea SD and Pine SD displaying the greatest potential for lowering emissions. This underscores the necessity of implementing biomass co-firing as a sustainable approach to combat climate change and lessen the carbon footprint of industrial activities.

Characterization	10% cofiring	15% cofiring	20% Cofiring
CV in kcal/kg	6037.976	5944.644	5851.312
MC in %	0.235	0.3525	0.47
VM in %	28.09	30.585	33.08

ASH in %	20.832	19.783	18.734
FC in %	50.843	49.2795	47.716
Sulfur %	0	0	0

Table 18 Proximate analysis and CV values of Olea SD.

Co-firing Olea SD with coal in cement kiln operations represents a viable and sustainable approach that provides substantial environmental and economic advantages. Although the calorific value of the fuel mixture slightly decreases with an increase in biomass percentages, the rise in volatile matter and the decrease in ash and sulfur content more than offset this. A co-firing ratio of 15-20% is suggested as the ideal equilibrium between efficiency, emissions reduction, and operational feasibility. This strategy is in line with worldwide initiatives aimed at lowering GHG emissions and moving toward more sustainable industrial practices.

Ultimate analysis in %	10%	15%	20%
Hydrogen	4.010978	4.105168	4.199359
Carbon	73.28448	71.86228	70.44008
Nitrogen	1.956661	1.888513	1.820365
Oxygen	20.05248	21.48566	22.91884
Sulphur	0.695405	0.658383	0.62136

Table 19 Proximate analysis and CV values of Pine SD

Characterization	10% cofiring	15% cofiring	20% Cofiring
CV in kcal/kg	6060.476	5978.394	5896.312
MC in %	0.238	0.357	0.476
VM in %	29.02	31.98	34.94
ASH in %	20.68	19.555	18.43
FC in %	50.062	48.108	46.154
S in %	0	0	0

Table 20 Ultimate analysis Olea SD

Ultimate analysis in %	10%	15%	20%
Hydrogen	4.028026	4.13074	4.233455
Carbon	73.20913	71.74926	70.28938

Nitrogen	1.965961	1.902463	1.838965
Oxygen	20.10352	21.56222	23.02092
Sulphur	0.693365	0.655323	0.61728

Table 21 Ultimate analysis Pine SD

4.1.2. Numerical Analysis results of each sample at cofiring ratio based on an excel calculation

parameter	10%	15%	20%
A/F in Kg/Kg	9.988893136	9.762687318	9.5364815
EAR in %	1.997778627	1.952537464	1.9072963
O req kg/kg	2.097667559	2.050164337	2.002661115
CO2 kg/kg	2.683086812	2.62893421	2.574781607
SO2 kg/kg	0.013915306	0.013178456	0.012441606
NOX Kg/kg	0.009810806	0.009483817	0.009156827

Table 22 Eucalyptus at cofiring ratio

parameter	10%	15%	20%
A/F	6.035492873	9.787396437	9.569426992
EAR	1.207098575	1.957479287	1.913885398
O req	1.277202333	2.055353252	2.009579668
CO2	2.7097449	2.634950165	2.582802881
SO2	0.013908106	0.013167656	0.012427206
NOX	0.009783306	0.009442567	0.009101827

Table 23 Olea SD at Cofiring ratio

parameter	10%-	15%	20%
A/F	10.00020777	9.779659271	9.55911077
EAR	2.000041554	1.955931854	1.911822154
O req	2.101126835	2.055353252	2.009579668
CO2	2.74334726	2.63080608	2.577277434
SO2	0.013867306	0.013106456	0.012345606
NOX	0.009829806	0.009512317	0.009194827

Table 24 Pine SD at cofiring ratio

The numerical analysis presents essential parameters such as air-to-fuel ratio (A/F), excess air ratio (EAR), oxygen requirement (O req), and emissions (CO_2, SO_2, and NO_x) for each co-firing ratio.

Air-to-Fuel Ratio (A/F): Slightly declines with increased biomass co-firing ratios, as biomass needs less air for combustion.

Excess Air Ratio (EAR): Decreases with greater biomass percentages, as biomass combustion proves to be more efficient.

Oxygen Requirement (O req): Reduces with increased biomass co-firing, owing to biomass's higher oxygen content.

CO_2 Emissions: Decline with larger biomass proportions, as biomass contains lower carbon content.

SO_2 Emissions: Stay negligible across all co-firing ratios, since biomass lacks sulfur content.

NO_x Emissions: Exhibit a slight decrease with higher biomass co-firing, due to biomass's lower nitrogen content.

Environmental Benefits:

Lower Carbon and Sulfur Emissions: Biomass substitution markedly lowers CO_2 and SO_2 emissions, aiding in cleaner air and diminished climate impact.

Improved Combustion Characteristics: Increased volatile matter boosts combustion efficiency, shortening ignition time and enhancing responsiveness.

Reduced Ash Deposition: Lower ash levels enhance operational efficiency and decrease maintenance costs in cement kilns.

Operational Considerations:

Slight Reduction in Energy Content: The decreased CV of biomass necessitates minor adjustments in fuel input to sustain the same heat output.

Moisture Management: The increased moisture content in biomass requires careful drying and management to preserve flame stability and combustion efficiency.

Optimal Co-Firing Ratio:

15-20% Co-Firing: Achieves the optimal equilibrium between emissions reduction, energy efficiency, and operational feasibility. This range maximizes environmental advantages while minimizing effects on kiln performance.

Co-firing biomass (Eucalyptus SD, Olea SD, and Pine SD) with coal in cement kiln operations constitutes a technically viable and environmentally sustainable approach. The data indicates that higher biomass co-firing ratios (15-20%) result in considerable decreases in CO_2, SO_2, and NO_x

emissions, while also enhancing combustion efficiency and minimizing ash deposition. Although the calorific value of the fuel mix experiences a slight decline with increased biomass proportions, this is compensated by the higher volatile matter content and superior combustion characteristics.

4.1.2. Emission analysis

Parameter	10%	15%	20%
CO2	3.87997	5.81996	7.759942
SO2	9.57632	14.3645	19.15264
NOX	6.24933	9.37399	12.49865

Table 25 Olea SD emission reduction

parameter	10%	15%	20%
CO2	3.73629	5.60444	7.472585
SO2	9.62311	14.4347	19.24622
NOX	6.51211	9.76817	13.02422

Table 26 Pine SD emission reduction

CO_2 Reduction: Increases in a linear manner, attaining 7. 670531 units at 20% co-firing.

SO_2 Reduction: Demonstrates a notable decrease, reaching 19. 77646 units at 20% co-firing.

NO_x Reduction: Grows consistently, reaching 12. 13553 units at 20% co-firing.

Pine SD co-firing offers the greatest SO_2 reduction among the three biomass types, rendering it especially effective for mitigating acid rain and air pollution.

The decrease in CO_2 and NO_x emissions is also considerable, aiding overall environmental sustainability.

Biomass Type	CO_2 Reduction (20%)	SO_2 Reduction (20%)	NO_x Reduction (20%)
Eucalyptus SD	7.759942	19.15264	12.49865
Olea SD	7.472585	19.24622	13.02422
Pine SD	7.670531	19.77646	12.13553

Table 27 comparative analysis

CO_2 Reduction: Each of the three biomass types exhibits comparable trends in CO_2 reduction, with Eucalyptus SD having a minor advantage.

SO_2 Reduction: Pine SD offers the greatest SO_2 reduction, succeeded by Olea SD and Eucalyptus SD.

NO_x Reduction: Olea SD demonstrates the highest level of NO_x reduction, trailed by Eucalyptus SD and Pine SD.

4.1.3. Economic Overview

Amount of Fuel Required

The total fuel consumption in cement manufacturing significantly affects both the profitability of the company and the consumption of natural resources. Thus, choosing a fuel source that delivers greater energy output per unit mass is vital for enhancing efficiency and sustainability. Biomass fuels, like co-fired eucalyptus sawdust (SD), present a promising substitute for conventional coal, even though they have a marginally lower calorific value. The quantity of fuel needed to produce a set amount of clinker in the kiln pyro-processing is determined by the fuel's energy content. For example, while coal has a superior calorific value, biomass co-firing can still be an effective alternative due to its eco-friendly advantages.

Based on calculations from the carbon dioxide emission formula, it was found that the combustion of 1 kg of 10% co-fired eucalyptus SD results in the production of 5. 779 kg of cement, whereas 1 kg of coal produces 6. 107 kg of cement. This indicates that 0. 17304 kg of co-fired eucalyptus SD is necessary to generate 1 kg of cement, in contrast to 0. 16374 kg of coal for the same quantity of cement. Although the fuel requirement for eucalyptus SD is marginally greater, the decrease in coal utilization and the related environmental advantages render it a sustainable choice.

The percentage reduction in coal usage when substituting 10% eucalyptus SD is calculated as follows:

$$\% \text{ of fuel decrease} = \frac{\text{difference}}{\text{Initial usage}} * 100 = \frac{0.93}{16.374} * 100 \text{…………………………Eq 13}$$

$$\% \text{ of reduction} = 5.6\%$$

This suggests that utilizing 10% co-fired eucalyptus SD can substitute 5. 6% of coal, thus decreasing the exhaustion of non-renewable fossil fuels. Furthermore, this method encourages energy recovery from waste products, like sawdust, which would otherwise result in environmental contamination. By incorporating biomass into the fuel composition, the cement sector can attain a cleaner and more sustainable manufacturing process.

4.1.4. Flame Temperature

When assessing fuel replacement choices in the cement sector, a pivotal aspect is the capacity of the substitute fuel to reach the necessary flame temperature for pyro-processing. The kiln generally functions at temperatures between 1400°C and 1750°C, which is essential for effectively combusting raw materials and creating clinker. At Messebo Cement Factory, the kiln functions at 1450°C. According to calculations performed in Excel, 10% co-fired eucalyptus sawdust (SD) reaches a flame temperature of around 1770 K (1497°C), which is adequate to fulfill the kiln's operational needs. This illustrates that eucalyptus SD is a feasible alternative fuel for cement manufacturing.

Energy Consumption and Cost Implications

The implementation of alternative fuels (AF) within the cement sector is closely connected to the energy-demanding procedure of clinker manufacturing. On average, the energy needed to generate 1 kg of cement is about 3300 kJ. This energy requirement equates to the use of 0. 1637 kg of coal or 0. 17304 kg of co-fired eucalyptus SD per kg of cement. Although the fuel requirement for eucalyptus SD is marginally greater, the economic and environmental advantages of using biomass surpass this variation.

Energy expenditures represent 30-40% of the overall production expenses in the cement industry. By incorporating alternative fuels such as eucalyptus SD, cement facilities can notably decrease their production costs. For example, Messebo Cement Factory presently acquires coal from South Africa at a price of 10 birr per kg, not including transportation and tax costs. This indicates that 1. 637 birr worth of coal is incinerated to produce 1 kg of cement. Conversely, eucalyptus SD, priced at an average of 2. 25 birr per kg, necessitates only 0. 38205 birr worth of fuel to manufacture the identical quantity of cement. This indicates a considerable cost reduction, making eucalyptus SD a financially appealing substitute. Generally,

i. Flame Temperature Suitability: Co-firing 10% eucalyptus SD achieves a flame temperature of 1770 K (1497°C), which satisfies the kiln's operational requirements of 1450°C.

ii. Energy Efficiency: The energy needed for clinker manufacturing is 3300 kJ per kg of cement, which can be fulfilled by both coal and eucalyptus SD.

iii. Cost Savings: Using eucalyptus SD decreases fuel expenses from 1. 637 birr per kg of cement (coal) to 0. 38205 birr per kg of cement (eucalyptus SD), reflecting a considerable economic advantage.

iv. Environmental Benefits: Co-firing eucalyptus SD diminishes dependence on non-renewable coal, reduces greenhouse gas emissions, and encourages sustainable waste usage.

The integration of alternative fuels such as eucalyptus SD into the cement industry presents a practical approach to satisfy the energy and temperature demands of kiln pyro-processing while lowering production costs and environmental effects. At Messebo Cement Factory, co-firing 10% eucalyptus SD meets the required flame temperature and delivers significant cost reductions in comparison to coal. This shift not only improves the economic feasibility of cement production but also corresponds with global initiatives to foster sustainability and lower carbon emissions.

Amount of Cement produced	Fuel cost (birr)	
	Coal	Eucalyptus
per 1Kg	1.637	0.38205
per 100kg	163.7	38.205

Table 28 Fuel costs comparison

Coal Fuel Cost per Year (Baseline)

$$
\begin{aligned}
&\mathit{Total\ Coal\ Cost}\\
&\qquad = \mathit{Coal\ Cost\ per\ kg\ Cement} \times \mathit{Cement\ Production\ per\ Year}\ 1.637 \times (2{,}000\\
&\qquad \times 1{,}000) \times 300\ = 982{,}200{,}000\ \mathit{birr\ per\ year}
\end{aligned}
$$

The above table illustrates the economic viability of using waste eucalyptus in the cement industry. The factory runs 300 days a year, according to Messebo's official website. The calculations show that using eucalyptus instead of coal can save about 75,297,000 birr a year, which is calculated using the following formula:

(1,637 - 382.05) × 2,000 tons in line one × 300 = 75,297,000 birr. These savings are on top of lower transportation and tax costs.

Fuel	10%	15%	20%
Eucalyptus	75,297,000	112,980,000	150,600,000
Olea	74,154,000	111,576,000	149,070,000
Pine	74,718,000	112,734,000	150,546,000

Table 29 Amount of fuel saved per year

Type of Fuel	10%	15%	20%
Eucalyptus	7.66615761	11.5027489	15.3329261
Olea	7.54978619	11.3598045	15.1771533
Pine	7.60720831	11.4777031	15.3274282

Table 30 Percentage **of fuel cost reduction when blended with coal**

Environmental Benefits

The incorporation of biomass as a substitute fuel in cement manufacturing provides multiple environmental benefits:

Decrease in SO_2 and NO_x emissions: Biomass has minimal sulfur content, which results in reduced emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in comparison to coal burning.

Reduced reliance on fossil fuels: The partial substitution of coal with biomass lessens total coal usage, diminishing dependency on non-renewable fossil fuels and encouraging sustainable energy options.

Economic Benefits

Fuel Cost Comparison

A cost comparison between coal and eucalyptus as alternative fuel sources reveals significant savings:

- Coal cost: 1.637 birr/kg of cement.
- Eucalyptus cost: 0.38205 birr/kg of cement.
- Annual savings: By replacing 10% of coal with eucalyptus, approximately 75,297,000 birr can be saved per year.

Fuel Savings and Fossil Fuel Reduction

The decrease in coal usage when co-firing with eucalyptus leads to significant fossil fuel savings:

- 10% eucalyptus co-firing: Lowers coal usage by 5. 6%.
- 20% eucalyptus co-firing: Causes an additional reduction in fossil fuel reliance, enhancing the economic and ecological advantages of biomass integration.

4.2. Discussion

The results of this research indicate that co-firing eucalyptus, olea, and pine sawdust (SD) with coal serves as a feasible method for cement manufacturing, providing technical, economic, and ecological advantages. The examination verifies that the calorific values of these alternative fuels are adequately high to satisfy the energy needs for clinker production, while the flame temperature of about 1770 K guarantees optimal kiln functioning. Below are the essential factors endorsing the viability of biomass co-firing in the cement sector:

1. CO_2 Reduction Potential

Even with a 10% co-firing ratio, considerable reductions in CO_2 emissions are attainable. This correlates with global climate change mitigation efforts and aids the cement industry's shift towards low-carbon production practices. By substituting a portion of coal with biomass, the carbon footprint of cement manufacturing can be significantly decreased.

One of the most significant outcomes of this study is the marked reduction in carbon dioxide (CO_2) emissions associated with biomass co-firing. Biomass is considered carbon-neutral in lifecycle accounting since the CO_2 released during combustion was previously captured during plant growth. This contrasts with coal, which introduces geologically sequestered carbon into the active cycle. At just a 10% substitution level, the CO_2 emission per kilogram of cement is reduced from 0.760 kg (coal only) to 0.46426 kg (eucalyptus co-firing), corresponding to a 0.304875% emission reduction. This reduction scales linearly with increasing co-firing ratios, reaching over 1% at a 20% co-firing level with olea and pine. While the percentage reductions may appear modest, they represent substantial absolute emissions savings when applied across large-scale cement operations. This aligns with Ethiopia's climate goals and global efforts to decarbonize the cement sector, which is responsible for approximately 7–8% of global CO_2 emissions.

2. Fuel Efficiency

Although biomass fuels typically exhibit a lower calorific value compared to coal, their elevated volatile matter content boosts combustion efficiency. This offsets the difference in energy density, ensuring that the total energy output remains adequate for cement manufacturing processes.

Cement kiln pyroprocessing has significant energy requirements, necessitating fuels with high and consistent calorific values to sustain clinker production and maintain kiln flame temperatures. Despite having lower energy densities than coal, sawdust from eucalyptus, olea, and pine trees has high enough calorific values and a high enough volatile matter content to facilitate combustion. According to the study, the resulting flame temperature reaches roughly 1770 K at a 10% co-firing rate with eucalyptus sawdust, which completely satisfies the thermal requirements of clinker formation. This confirms that partial substitution is technically feasible without sacrificing clinker quality or process effectiveness.

Furthermore, biomass's higher volatile content encourages more thorough burning and enhances combustion stability. In cement kilns, where quick combustion and heat transfer are crucial, this is especially advantageous. In actuality, this suggests that biomass not only partially offsets the energy contribution of coal but also improves combustion kinetics, thereby compensating for the difference in calorific value.

3. Economic Viability

The price of eucalyptus and other biomass fuels is considerably lower than that of coal, rendering them a cost-efficient alternative. The economic assessment indicates that substituting 10% of coal with eucalyptus can yield savings of roughly 75,297,000 birr annually. These savings, along with diminished transport and tax costs, underscore the financial benefits of embracing biomass co-firing.

The incorporation of biomass fuels, particularly sawdust from eucalyptus and pine, makes a strong economic case. Significant operating savings are achieved when local biomass supply and reduced fuel prices are combined. In particular, eucalyptus may save about 75.3 million birr a year when 10% of coal is replaced with it. At a 20% co-firing ratio, the savings rise to over 150 million birr. In addition to the lower cost of biomass per kilogram (e.g., 0.38205 birr/kg of cement for eucalyptus), these savings are also a result of lower costs for the procurement, transportation, and related emissions penalties of coal. Reduced coal usage, which drops by 5.6% at the 10% co-firing level, and possible tax breaks or carbon credits associated with lower emissions provide additional financial advantages.

4. Environmental Benefits

Besides CO_2 reductions, co-firing biomass with coal results in decreased emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). This enhancement in air quality not only favors public health but also assists cement producers in adhering to increasingly stringent environmental regulations.

Cofiring biomass provides quantifiable reductions in other hazardous pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), in addition to mitigating greenhouse gas emissions. 20% eucalyptus co-firing can lower SO_2 emissions by 19.15 units and NO_x emissions by 12.50 units, according to the study. Of the fuels that were tested, olea sawdust produced the biggest NO_x reduction (13.02 units) and pine sawdust the most significant reduction in SO_2 (19.77 units). These cuts are essential for enhancing local air quality, lowering health hazards to surrounding communities and employees, and guaranteeing adherence to changing environmental regulations. In addition to reducing particulate matter generation and limiting equipment fouling, lower sulfur and ash concentrations in biomass (e.g., ash content of 18.67% at 20% co-firing) also help to improve kiln operation and save maintenance costs.

5. Scalability and Implementation

The findings imply that increasing biomass co-firing to 15% or 20% replacement rates can further improve both the environmental and economic outputs of cement production. However, effective implementation necessitates tackling logistical issues, such as managing the biomass supply chain and ensuring consistent fuel quality.

Although the results clearly support the use of biomass co-firing, logistical and operational considerations must be carefully taken into account for successful deployment. Maintaining combustion efficiency requires homogeneity in particle size, fuel moisture regulation, and biomass supply chains. Fuel property variation can impact emissions and kiln stability, requiring strict quality control and possible improvements to fuel handling and feeding systems. Furthermore, because biomass burns differently than coal, the air-fuel ratio, oxygen demand, and excess air levels need to be modified. For instance, because of its advantageous combustion properties, pine sawdust lowers the necessary oxygen levels and air-to-fuel ratio. Because of these operational modifications, biomass co-firing is a realistic improvement rather than a huge infrastructure change that may necessitate modest retrofits or recalibration of combustion controls rather than a disruptive overhaul.

In summary, the co-firing of sawdust from pine, olea, and eucalyptus shows great promise for achieving economic and environmental objectives without sacrificing technical performance in the cement production process. Because of its ability to reduce emissions, local availability, and burning behavior, pine sawdust stands out among the studied options as the most scalable and balanced biomass alternative. The overall findings provide biomass co-firing as a viable and significant route toward decarbonizing cement production in Ethiopia and beyond, even though supply chain management and technological modifications are essential for success.

5. RECOMMENDATION

Based on the results of this research, the following suggestions are made to improve the adoption and effectiveness of biomass co-firing in the cement sector:

1. Scale-Up Co-Firing Beyond 10%

To optimize the environmental and economic advantages, cement producers should consider increasing biomass co-firing rates past the 10% replacement threshold. Raising the co-firing rate to 15% or 20% can further minimize CO_2 emissions and lessen dependence on coal, aiding both climate efforts and financial savings.

2. Pilot Testing at Industrial Scale

Prior to large-scale implementation, pilot testing should be performed to optimize operational parameters such as fuel mixing ratios, combustion temperatures, and kiln efficiency. This will assist in identifying and resolving any technical issues, ensuring the seamless integration of biomass co-firing into existing manufacturing processes.

3. Explore Alternative Biomass Sources

Although eucalyptus, olea, and pine sawdust have demonstrated favorable outcomes, further investigation into other biomass sources with high energy content is suggested. Recognizing locally accessible and sustainable biomass alternatives can enhance the economic and environmental advantages of co-firing while diversifying fuel options.

4. Policy Incentives and Regulatory Support

Government entities and regulatory agencies should establish policy incentives, like tax benefits, subsidies, or carbon credits, to promote the adoption of biomass co-firing in the cement sector. Supportive regulations can expedite the shift to sustainable energy practices and align the industry with national and global climate objectives.

5. Further Research on Fuel Mixing Ratios

More research is required to ascertain the optimal fuel mixing ratios that balance energy efficiency, cost-effectiveness, and environmental sustainability. Examining the long-term effects of various biomass-coal blends on kiln efficiency and clinker quality will yield valuable insights for expanding co-firing initiatives.

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7. APPENDICES

7.1. Appendix A . description of the cement kiln pyro processing system

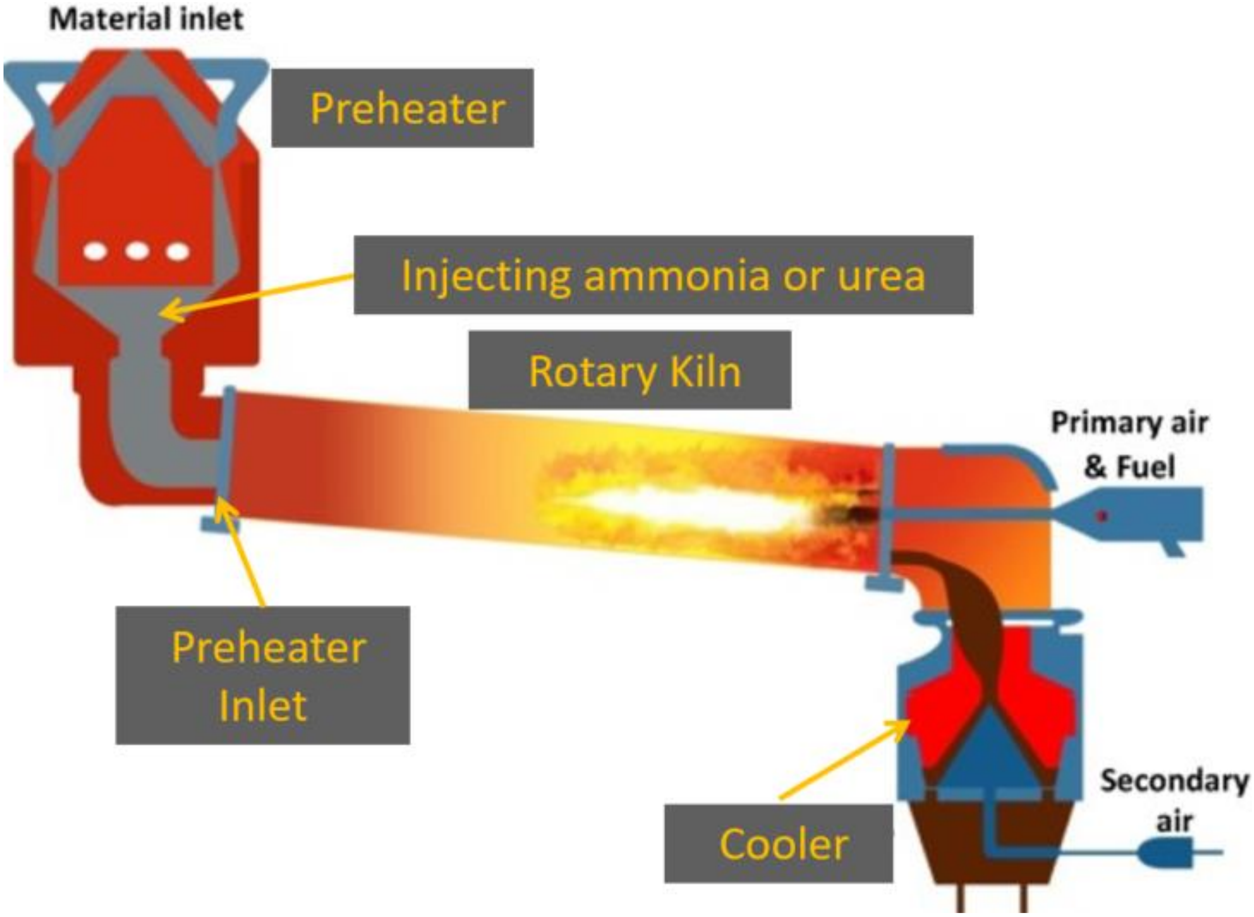

Figure 8 **cement kiln pyro processing system**

- The preheater is a series of cyclone chambers that preheat the raw materials by exchanging heat with the hot exhaust gas from the kiln. The preheater reduces the energy consumption and the CO2 emissions of the kiln, and improves the quality and homogeneity of the raw materials.
- The rotary kiln is a long cylindrical vessel that rotates on its axis and is slightly inclined. The raw materials enter the kiln from the upper end and move downwards by gravity. The kiln is heated by a burner at the lower end, where the fuel and the combustion air are injected. The kiln temperature can reach up to 1450 °C, which is enough to trigger the chemical reactions that form the clinker. The kiln is the heart of the pyroprocessing system, where the main energy consumption and greenhouse gas emissions occur.
- The clinker cooler is a device that cools down the hot clinker from the kiln by exchanging heat with ambient air. The clinker cooler recovers most of the heat from the clinker, which can be used for preheating the raw materials or generating electricity. The clinker cooler

also improves the quality and grindability of the clinker, and reduces the thermal stress and wear of the kiln refractory.

- The exhaust gas treatment is a system that cleans the exhaust gas from the kiln and the cooler before releasing it to the atmosphere. The exhaust gas treatment removes the dust, the sulfur dioxide, the nitrogen oxides, and other pollutants from the gas, and reduces the environmental impact of the pyroprocessing system.

7.2. Appendix B. Technical, Environmental and Economic Feasibility Analysis of Coal, Pet Coke and Pine Sawdust

7.2.1. Methods and Procedures

The methods and procedures that were used to perform the technical, environmental and economic feasibility analysis are described in this section. The methods and procedures include the data sources, the models, the assumptions, the criteria, and the indicators.

7.2.2. Data Sources

The data sources include the literature, the web search results, and the experimental data.

Data Type	**Data Source**	**Description**
Fuel Properties	Literature	The physical and chemical properties of coal, pet coke and pine sawdust, such as the proximate and ultimate analysis, the higher and lower heating value, and the thermogravimetric analysis.
Combustion Characteristics	Literature	The combustion characteristics of coal, pet coke and pine sawdust, such as the ignition temperature, the burnout temperature, the combustion efficiency, and the flame stability.
Emission Factors	Literature	The emission factors of coal, pet coke and pine sawdust, such as the CO2, SO2, NOX, and PM emissions per unit of energy.
Economic Parameters	Web Search Results	The economic parameters of coal, pet coke and pine sawdust, such as the fuel cost, the electricity revenue, the discount rate, and the carbon credit.

Experimental Data	Experimental Data	The experimental data of the co-firing of coal, pet coke and pine sawdust, such as the heating value, the combustion characteristics, and the emission reduction of the co-fired fuel.

Table 31 Data sources for the technical, environmental and economic feasibility analysis

7.2.3. Assumptions

The assumptions include the co-firing ratio, the heating rate, the temperature, the oxygen concentration, and the emission factors.

Assumption	**Value**	**Source**
Temperature	25-1000 °C	Literature
Oxygen Concentration	21%	Literature
CO2 Emission Factor	0.056 kg/MJ	Literature
SO2 Emission Factor	0.064 kg/MJ	Literature
NOX Emission Factor	0.07 kg/MJ	Literature

Table 32 Assumptions for the technical, environmental and economic feasibility analysis

7.2.4. Criteria

The criteria include the technical performance, the environmental impacts, and the economic viability of the co-fired fuel.

Criterion	**Description**
Technical Performance	The technical performance of the co-fired fuel was evaluated by comparing the heating value, the combustion characteristics, and the flame stability of the co-fired fuel with the coal-only fuel. The co-fired fuel was considered technically feasible if it had a comparable or higher heating value, a comparable or lower ignition and burnout temperature, a comparable or higher combustion efficiency, and a stable flame.
Environmental Impacts	The environmental impacts of the co-fired fuel were evaluated by comparing the emissions of the co-fired fuel with the coal-only fuel. The co-fired fuel was considered environmentally feasible if it had a lower CO2, SO2, NOX,

	and PM emissions per unit of energy, and a higher emission reduction potential.

Table 33 ***criteria for the technical, environmental and economic feasibility analysis***

Equations used: Ultimate analysis

a. $C = 0.637 * FC + 0.455 * VM$
b. $H = 0.052 * FC + 0.062 * VM$
c. $N = 0.01 * VM$
d. $S = 0.01 * Ash$

Proximate analysis

$LHV\ in \frac{MJ}{Kg} = HHV - \left(9 * \frac{H}{100} * 2.442\right) where\ 2.442\ is\ latent\ heat\ of\ vaporization\ of\ water$

Or $LHV = HHV - 21.97 * H$

$AFR\ in \frac{kg}{kg} = \frac{100}{C+0.375*H-0.375*O+0.1*S}$ or $AFR = \left(\frac{C}{12} + \frac{H}{4} + \frac{S}{32}\right) * 32$ or $AFR = (C + 0.375 * S) + 8 * \frac{H-0.125*O}{O2} in\ air$,$23\ \% = 0.23$

I1kca/kg=0.004184MJ/kg

$EAR\ in \frac{kg}{kg} = (Actual\ air - Theoretical\ air), excess\ is\ taken\ as\ 20\ to\ 30\ \%$ or EAR=AFR*%Excess which 20% commonly taken air

$$FT = Ti + \frac{LHV * Efficiency}{Cp}$$

Emission $CO2 = C * \frac{44}{12}$

$Tf = T0 + CpLHV \times \eta$ or $Tf = Q/mCp + Ti$ Q heat released , m mass of combustion products

where:

- T0 is the initial temperature (usually taken as 298K).
- η\etaη is the combustion efficiency (assume 85%).
- Cp is the specific heat of flue gas (assume 1.04 kJ/kgK).
- $Tad = 3660 + 10.9 * LHV - 17.3 * (Ash + Moisture)$

7.2.4. Experimental results

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Date: 19/06/2024
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REF.No: MCMe/2123/8·6/24

TO: Mekelle University
School of Mechanical and Industrial Engineering.

Subject: **The Calorifc Value and Proximate analysis of "different Samples" Analysis Confirmation.**

According to the request (Ref.No: smic000344/2024G.C, dated June 04, 2024) to cooperate **Guesh Tewele** to conduct the calorific value and proximate analysis of **"different Samples"** in our laboratory.

Hence, the analysis result of **"different Samplles"** according to our laboratory Calorific Value and proximate analysis Procedure is tabulated below.

The Calrific Value and proximate analysis of Samples Results.

S/No	Sample Code	Calorific Value(kcal/kg)	Inherent moisture (%)	Volatility (%)	Ash (%)	Fixed Carbon (%)	Remark
01	Eucalyptus	4164.00	2.80	78.50	1.63	17.07	
02	Olive	4358.00	2.35	73.00	1.95	22.70	
03	Pine	4583.00	2.38	82.30	0.43	14.89	

With best regards,

Hadushalem Kahsay
Plant Operation Manager

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Quality in Action
Messebo Cement Factory plc

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ISO 9001: 2015 & 14001: 2015 Certified Company, Certificate No- 18429