MEKELLE UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

DEPARTMENT OF CHEMISTRY

A M.Sc. Thesis on:

EVALUATION OF AIR POLLUTION CONTROL TECHNIQUES IN MESSEBO CEMENT FACTORY, TIGRAY, ETHIOPIA

Submitted to the College of Natural and Computational Science, Department of Chemistry, in partial fulfillment of the requirements for the Degree of Master of Science in Chemistry (Analytical Chemistry)

By: Araya Gebreyohannes
Under the supervision of

Advisor: Prof. Abraha Gebrekidan (Ph.D.)

Co-Advisor: Mr. Amanual Hadera (M.Sc., Assist. Prof.)

September 2025

ACKNOWLEDGEMENTS

First and foremost, I extend my profound gratitude to Almighty God for His endless blessings and guidance throughout my academic endeavors.

I would like to extend my heartfelt gratitude to my advisor, Prof. Abraha Gebrekidan, and my co-advisor, Amanual Hadera, for their unwavering support, kindness, and exceptional guidance during my thesis work. Their insightful feedback, encouragement, and expert advice have been invaluable throughout this research process. I would also like to acknowledge Dr. Takele Achalu, whose invaluable support and expertise significantly contributed to the success of my research.

Additionally, I am grateful to several individuals from both the academic and industrial communities who have shared their insights and provided feedback that greatly enhanced this study. Special thanks go to Assefa Hadush, an environmentalist at Messebo Cement Factory PLC, and the process engineers Muruts and Yirga from the Coal and Kiln Department, Cement Factory PLC, as well as Ato Gebremedhin from the Health and Safety Department, Cement Factory PLC, for their practical advice and assistance during the course of my research.

I would also like to express my appreciation to my colleagues and friends, Tetemke Gebremedhin and Temesgen Gebreamlak, whose support and invaluable input played a significant role in shaping the outcome of this research. Finally, I would like to express my deepest gratitude to my family for their continuous encouragement and support. Special thanks to my beloved wife, Alemtsehay, whose love, patience, and unwavering belief in me have been a source of strength. I am also grateful to my family members, Dr. Haben, Buruk, Henon, Eyosyas, Nelawi, and Rufta, for their constant support throughout my academic career.

Acronyms

CMP – Cement mill and packing

EFFORT - Endowment Fund for Rehabilitation of Tigray

HCRDI - Heifi Cement Research and Design Institute

LHHSR - Low Heat of Hydration Sulphate Resistant

MACT- Maximum Achievable Control Techniques

MCF - Messebo Cement Factory

OPC - Ordinary Portland cement

PM-Particulate Matter

PIC - Product of Incomplete Combustion

PLC - Portland Limestone Cement

PMCD - Particulate matter of clinker dust

PPC - Pozzolana Portland cement

TSP- Total Suspended Particle

VOCs – Volatile organic carbon compounds

MACT - Maximum Achievable Control Technology

Table of Contents

LIST OF TABLES

List of Figures

Abstract

Cement production is one of the most emission-intensive industrial activities, contributing significantly to global air pollution and greenhouse gas emissions. This study assesses the effectiveness, limitations, and implementation status of air pollution control techniques and their associated occupational health impacts at Messebo Cement Factory PLC (MCF) in Northern Ethiopia. A mixed-method design was employed, integrating quantitative on-site pollutant measurements (CO_2, NO_x, SO_2, CO, and particulate matter) with qualitative surveys and clinical health data. Field results indicated that pyroprocessing and raw material handling were the dominant emission sources. CO_2 emissions increased from approximately 78,884 tonnes in 2000/01 to 990,767 tonnes in 2015/16, primarily due to production expansion, while per-tonne emissions remained above international best practice benchmarks. Particulate matter concentrations at raw milling points reached 240 mg/Nm^3, exceeding Ethiopia's national limit of 150 mg/Nm^3 and the WHO/IFC guideline of 50 mg/Nm^3. Despite the presence of baghouse filters and other emission control systems, frequent exceedances revealed operational inefficiencies and maintenance deficiencies. Survey data from 1,235 respondents, including factory employees and nearby residents, showed that 65% observed visible dust emissions and 76% reported receiving no environmental or safety training. Analysis of clinical records from 2013–2017 further revealed high incidences of respiratory tract infections (up to 22.4%) and dermatitis linked to particulate exposure. The findings demonstrate that current air pollution control and occupational health practices at MCF are inadequate to meet regulatory and safety standards. The study recommends upgrading filtration systems, adopting cleaner fuels, improving occupational health and safety management, and aligning operations with ISO 14001 and IFC/World Bank environmental standards to promote sustainable industrial performance.

Keywords: Air pollution, Cement industry, Emission control, Occupational health, Environmental management, Ethiopia

CHAPTER 1: INTRODUCTION

1.1. Background of the Study

Cement production is one of the most emission-intensive industries worldwide, contributing significantly to greenhouse gas (GHG) emissions and air pollution. Globally, the sector accounts for approximately 7–8% of total anthropogenic CO_2 emissions, largely due to limestone calcination and fossil fuel combustion in high-temperature kilns (IEA, 2020; Andrew, 2018; Liu et al., 2024). In addition to CO_2, cement plants release nitrogen oxides (NO_x), SO_2, particulate matter (PM), CO, and volatile organic compounds (VOCs), which adversely affect air quality, public health, and ecosystem stability (WHO, 2006; USEPA, 2010). These global concerns have shaped international environmental frameworks such as the Paris Agreement, United Nations Framework Convention on Climate Change (UNFCCC), and World Health Organization (WHO) air quality guidelines, which increasingly require industries to adopt cleaner technologies and reduce emissions. Among the different production stages, pyroprocessing is the most energy- and emission-intensive, requiring kiln temperatures above 1400 °C, which facilitate NO_x formation and substantial CO_2 emissions (Van Oss & Padovani, 2002).

The environmental burden of cement manufacturing has placed the sector under increasing scrutiny within global climate frameworks such as the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC, 2015). The Intergovernmental Panel on Climate Change (IPCC, 2014) emphasizes that cement sector emissions are influenced by population growth, energy intensity, and carbon intensity, as illustrated by the Kaya Identity. Accordingly, stricter international and national regulatory standards, such as those issued by the World Health Organization (WHO, 2006), International Finance Corporation (IFC, 2007), and the Ethiopian Environmental Protection Authority (FDRE EPA, 2014), have sought to reduce industrial emissions.

In Ethiopia, the cement industry has expanded rapidly over the past two decades, driven by infrastructure growth and urbanization (Berhe et al., 2014). However, this expansion has been accompanied by rising environmental concerns. Local factories frequently struggle to comply with emission standards due to reliance on outdated technologies, weak monitoring capacity, and insufficient maintenance (Gebreslassie et al., 2023). Messebo Cement Factory (MCF), established in 1999 near Mekelle in the Tigray Region, is one of the country's largest producers, with an annual capacity exceeding 2 million tonnes of clinker (Gebrekidan & Abraha, 2022). While MCF plays an important role in Ethiopia's industrial development and post-conflict reconstruction, its environmental footprint has been a persistent concern. Long-term emission data indicate that CO_2 emissions increased from

78,884 tonnes in 2000/01 to nearly 991,000 tonnes in 2015/16, correlating strongly with production growth (Berhe et al., 2014).

Despite the adoption of control technologies such as bag filters and low-NO_x burners, surrounding communities continue to report dust deposition, reduced visibility, and adverse health effects linked to air pollution (UNEP, 2013). Previous studies have primarily focused on aggregate emission levels but have not systematically examined the operational performance of control technologies, consistency of regulatory compliance, or socio-environmental consequences. Furthermore, more recent developments since 2017, including production line changes, updated regulations, and community grievances, remain underexplored.

Against this backdrop, the present study seeks to provide an integrated evaluation of air pollution control techniques at MCF. Specifically, it aims to: (i) quantify gaseous and particulate emissions across production stages; (ii) assess the effectiveness of existing mitigation measures against Ethiopian EPA and World Health Organization/International Finance Corporation WHO/IFC standards; (iii) analyze workers' and local communities' perceptions regarding air quality and pollution control measures; and (iv) propose evidence based recommendations to strengthen regulatory compliance and promote sustainable industrial practices. By addressing both the technological and socio-environmental dimensions, this study fills a critical research gap in Messebo Cement Factory and contributes to the broader discourse on sustainable industrial development.

1.2. Statement of the Problem

The MCF, one of Ethiopia's largest cement producers, has been operating since 2000 GC with a production capacity exceeding 2 million tonnes of clinker annually. Despite its economic importance, MCF has faced persistent challenges in controlling air pollution. Although bag filters, cyclones, and other emission control systems are installed, frequent filter failures, inconsistent maintenance, and limited monitoring capacity have resulted in recurring emission levels above permissible limits. Past reports and partial assessments have documented rising CO_2 and particulate emissions, but there have been no comprehensive evaluations of the actual effectiveness of these control systems or their compliance with regulatory standards.

Nationally, EPA stipulates emission thresholds for CO_2, SO_2, NO_x, CO, and particulate matter, aligned in part with international standards set by WHO and IFC. However, reports indicate that MCF frequently surpasses these standards, raising concerns for both environmental quality and public health in the surrounding communities. Residents have reported dust deposition, visibility reduction, and respiratory health issues, suggesting that regulatory non-compliance has tangible socio-environmental impacts.

The unresolved problem is therefore twofold: first, the efficiency and reliability of MCF's current pollution control technologies remain uncertain; and second, there is limited integration of community perceptions and health impacts into the evaluation of emission control strategies. Previous studies largely focused on aggregate emission trends (2001–2017), with little attention to post-2017 developments, control system performance, or socio-environmental dimensions. This gap makes it difficult to assess whether current mitigation measures are effective or sustainable in the long term. This study addresses that gap by systematically evaluating the performance of emission control technologies at MCF, benchmarking emission levels against Ethiopian EPA, WHO, and IFC standards, and integrating community and workforce perspectives. By combining quantitative emission measurements with qualitative assessments, the research seeks to clarify compliance gaps, analyze the cost-effectiveness of existing measures, and identify evidence-based strategies for improving air quality management in Ethiopia's cement sector.

While cement production is essential to infrastructure development, it is also one of the leading contributors to environmental pollution, particularly through emissions of greenhouse gases and airborne particulates. MCF exemplifies this dual challenge. Emissions generated during various production phases, including raw material acquisition, pyroprocessing, clinker cooling, and cement milling, consist of CO_2, NO_x, SO_2, CO, and PM. These pollutants have been linked to serious environmental and health risks, including respiratory diseases, soil, and water contamination, and global warming. Although modern emission control technologies are available and partially implemented at MCF, no comprehensive study has been conducted to evaluate their actual effectiveness or adherence to national and international air quality standards. In the absence of empirical assessments, it remains uncertain whether current mitigation strategies are sufficient to reduce environmental harm.

1.3. Objectives of the Study

1.3.1. General objective

The general objective of this study is to assess the effectiveness, limitations, and implementation status of air pollution control techniques at Messebo Cement Factory PLC, Ethiopia.

1.3.2. Specific objectives

- To identify the main sources and types of air pollutants generated by the factory.
- To measure the levels of major air pollutants at different stages of cement production of MCF.
- To evaluate the effectiveness of the existing air pollution control techniques implemented by MCF.
- To identify technical and management-related challenges affecting pollution control performance.

CHAPTER 2: LITERATURE REVIEW

2.1. Cement Manufacturing and Associated Air Pollution

Cement manufacturing is a vital industrial process supporting global construction and infrastructure development (Ali et al., 2015). Despite its economic importance, it is widely recognized as a major contributor to environmental pollution. The manufacturing process encompasses several energy-intensive stages, such as raw material extraction, milling, pyroprocessing in rotary kilns, clinker cooling, and finish grinding, all of which release a range of air pollutants into the environment. These emissions include particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and greenhouse gases like carbon dioxide (CO_2), with significant implications for human health, air quality, and climate change (Van Oss & Padovani, 2002). In particular, the pyroprocessing stage, where limestone is calcined to form clinker accounts for the largest share of CO_2 emissions, due to both fuel combustion and the chemical decomposition of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$). Additionally, fugitive dust from material handling, grinding, and storage operations poses significant particulate pollution risks.

2.2. Types of Cement and Their Environmental Implications

Among the various types of cement, Ordinary Portland Cement (OPC) and Pozzolana Portland Cement (PPC) are the most prevalent in construction applications. Their distinct chemical compositions influence both mechanical performance and environmental reactivity (Murray & Price, 2008). Pozzolana Cement is a blended material composed of Portland cement and pozzolanic substances, siliceous or alumino-siliceous materials that, although not cementitious by themselves, react chemically with $Ca(OH)_2$ in the presence of water to form compounds with binding properties. The typical chemical constituents of PPC include: silica (SiO_2): 20–35%, alumina (Al_2O_3): 10–25%, iron oxide (Fe_2O_3): 2–8%, calcium oxide (CaO): 40–60%, magnesium oxide (MgO): 0–10%, sulfur trioxide (SO_3): 1–3% (Mishra et al., 2022). The OPC, on the other hand, is manufactured by heating a finely ground mixture of limestone and clay or shale to form clinker, which is then blended with gypsum to control the setting time. The typical chemical composition of OPC includes: lime (CaO): 60–67%, Silica (SiO_2): 17–25%, alumina (Al_2O_3): 3–8%, iron oxide (Fe_2O_3): 0.5–6%, magnesium oxide (MgO): 0.1–4%, sulfur trioxide (SO_3): 1–3%. Although both cement types contain similar oxides, their performance and environmental behavior differ. Pozzolana cement offers greater durability and enhanced resistance to chemical attacks, particularly in aggressive environmental conditions, making it suitable for marine and sewage-related constructions. Conversely, OPC is valued for its high early strength and rapid setting, making it ideal for general-purpose infrastructure projects (Neville, 2011; Hewlett & Liska, 2019).

The selection of cement type and its manufacturing method not only affects the mechanical properties of the final product but also significantly influences the magnitude and composition of air pollutants released during production. Clinker is the intermediate product in cement manufacturing, formed by heating a mixture of raw materials at approximately 1450 °C in the kiln. The primary materials include limestone, clay, shale, iron ore, and silica sand. The chemical composition of clinker determines the performance characteristics of the final cement, including strength development, setting time, and durability. The main chemical components of clinker are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF).

C_3S is the most abundant component of clinker and is responsible for the early strength development of cement. It reacts quickly with water to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). C_2S is the second most abundant component of clinker and is responsible for the later strength development of cement. It reacts more slowly than C3S but produces more C-S-H. C_3A reacts quickly with water to form calcium aluminate hydrate (C-A-H) and calcium hydroxide (CH). It is also responsible for the early setting of cement. C_4AF is responsible for the color of cement and contributes to its later strength development.

2.3. Cement Production Process and Emission Sources

Cement manufacturing is a complex, multi-stage industrial process that contributes significantly to air pollution due to its reliance on fossil fuels, high-temperature operations, and extensive material handling. The primary stages involved in this process include raw material acquisition and preparation, pyroprocessing, clinker cooling and storage, and finish milling and packaging, each of which emits specific types of pollutants. The process begins with raw material acquisition and preparation, where limestone, clay, shale, silica sand, and iron ore are extracted through surface mining methods such as open-pit and open-cast mining,. These raw materials are crushed, blended, and milled to produce a homogenous raw meal suitable for kiln feeding. During this stage, PM emissions are the primary environmental concern, arising from blasting, crushing, material transfer, and raw milling operations. Fugitive dust is particularly high in dry environments and in systems lacking dust enclosures, conveying covers, or proper filter technologies.

The pyroprocessing stage is the most energy-intensive and environmentally impactful part of the cement manufacturing process. It involves the preheating, calcination, and sintering of raw meal in rotary kilns at temperatures reaching approximately 1450 °C. During calcination, $CaCO_3$ decomposes to form CaO, releasing CO_2 as a major byproduct. This accounts for roughly 50% of total CO_2 emissions in the cement industry, while the remaining CO_2 is produced through combustion of fossil fuels like coal and petcoke. Furthermore, NO_x are formed during high-temperature combustion, particularly where flame temperatures exceed 1300 °C, promoting thermal NO_x formation. SO_2 emissions, although variable, depend on the sulfur content in raw materials and fuel, often released when sulfur-bearing compounds are oxidized during the preheater and calciner phases. Incomplete combustion or poor mixing of fuel and air can also result in CO emissions.

Following the formation of clinker, it must be rapidly cooled to preserve its mineralogical composition and allow for safe handling. During clinker cooling and storage, the hot clinker passes through grate or planetary coolers, where ambient air is used for heat recovery. However, this process can also generate substantial dust emissions, particularly if the cooler air is not adequately filtered before discharge. The cooled clinker is then transported to silos, where additional PM emissions may arise from pneumatic conveying and bucket elevator systems.

In the final phase, finish milling and packaging, the cooled clinker is ground with gypsum and sometimes supplementary cementitious materials such as pozzolana or limestone. This grinding process produces a fine cement powder, which is then stored in silos and dispatched either in bags or bulk. The handling and packaging stages are associated with significant particulate emissions, particularly if packaging machinery and loading systems are not enclosed or ventilated. In this stage, PM emissions are exacerbated by the very fine particle size of cement, where a large proportion of particles are smaller than 10 microns, posing health risks due to their inhalability (USEPA, 2010). Overall, each stage of cement production contributes to environmental pollution, both in the form of airborne particulates and hazardous gases. Effective emission control technologies such as bag filters, fabric filters, staged combustion, low-NO_X burners, and improved process control systems are essential to mitigate these impacts.The essential steps in cement production include quarrying limestone and other raw materials, preparing the raw mix through dosing, grinding, and homogenization, followed by calcination and clinkering, where chemical reactions occur between 850 °C and 1450 °C in the kiln. Afterward, the clinker is cooled, ground with gypsum and other additives to produce cement, and finally stored, packaged, and transported to the end user.

MCF produces four types of cement as per the demand of customers, namely OPC (ordinary Portland cement), PPC (Portland Pozzolana Cement), PLC (Portland Limestone Cement), and LHHSR (Low Heat High Sulfur Resistant) Cement.

2.4. Raw Materials of the Cement Manufacturing Process

Raw material of the cement industry is a huge industry, in which its raw material inputs are manufactured in three processes, raw material exploration, sources of raw materials, raw material mining. The exploration includes evaluation of geological, chemical, and topographical facts through the raw material sampling collected from trench and drilling sampling. In the exploration study must be include both quantity and quality of cement raw material in the place where selected (Mishra et al., 2022). The cement industry has six total raw materials as input to produce the final product, cement. Those raw materials are explored and mined at different sources of place, where the two main inputs, limestone and shale found on the hill of Messebo near the industry. Mining involves extracting raw materials from their source. There are two types of mining: underground and surface mining. The Messebo Cement Industry's mining department employs the surface mining method, which is furtherly divided into two types: Open pit mining: method involves clearing or relocating the overburden material before blasting. At Messebo Cement Industry, approximately 11 meters of overburden is removed from the land's surface before blasting limestone and shale. The industry employs this surface blasting technique for efficient extraction. In open-cast mining, blasting is conducted after removing the overburden material from the area to be mined. It is commonly used to extract materials such as gypsum, silica sand, iron ore, and pozzolana.

2.5. Raw Material Acquisition

The raw materials used are extracted from the earth through mining and quarrying and can be divided into the following groups: lime (calcareous), silica (siliceous), alumina (argillaceous), and iron (ferriferous). Since a form of calcium carbonate, usually limestone, is the predominant raw material, most plants are situated near a limestone quarry or receive this material from a source via inexpensive transportation. The plant must minimize the transportation cost since one-third of the limestone is converted to Carbon dioxide during the Pyro processing and is subsequently lost. Quarry operations consist of drilling, blasting, excavating, handling, loading, hauling, crushing, screening, stockpiling, and storing.

Raw Milling

Raw milling involves mixing the extracted raw materials to obtain the correct chemical configuration and grinding them to achieve the proper particle size to ensure optimal fuel efficiency in the cement kiln and strength in the final concrete product. Three types of processes may be used: the dry process, the wet process, or the semidry process. If the dry process is used, the raw materials are dried using impact dryers, drum dryers, paddle-equipped rapid dryers, air separators, or autogenous mills, before grinding, or in the grinding process itself. In the wet process, water is added during grinding. In the semidry process, the materials are formed into pellets with the addition of water in a pelletizing device.

Figure 1: Line two raw mill excess chimney of MCF cement production

Pyro-processing

In Pyro-processing, the raw mix is heated to produce Portland cement clinker. Clinkers are hard, gray, spherical nodules with diameters ranging from 0.32 - 5.0 cm (1/8 to 2") created from the chemical reactions between the raw materials. The Pyro-processing system involves three steps: drying or preheating, calcining (a heating process in which calcium oxide is formed), and burning (sintering). The Pyro-processing takes place in the burning/kiln department. The raw mix is supplied to the system as a slurry (wet process), a powder (dry process), or as moist pellets (semidry process). All systems use a rotary kiln and contain the burning stage and all or part of the calcining stage. For the wet and dry processes, all Pyro-processing operations take place in the rotary kiln, while drying and preheating, and some of the calcination is performed outside the kiln on moving grates supplied with hot kiln gases.

The cement formation process in the kiln may be divided into four stages, correlated with the temperature of the materials in the rotary kiln:

- Uncombined water evaporates from raw materials as material temperature increases to 100 ºC.
- As the material temperature increases from 100 ºC to approximately 900 ºC, dehydration and material heating occur.
- At 900 ºC, calcination occurs in which CO is liberated from carbonates.
- Following calcination, a chemical reaction of the dehydrated and decarbonated raw materials occurs in the burning zone of the rotary kiln at temperatures of about 1510 ºC, producing clinker. About 20% to 25% of the material is molten.
- The cement clinker continues to change in character as it passes the zone of maximum temperature.

Figure 2: Kiln line two of MCF cement production

Clinker Cooling

The clinker cooling operation recovers up to 30% of kiln system heat, preserves the ideal product qualities, and enables the cooled clinker to be maneuvered by conveyors. The most common types of clinker coolers are reciprocating grate, planetary (satellite), and rotary (tube).

The grate cooler is suited to large clinker capacities (up to 12,000 t of clinker per day). Air sent through the clinker to cool it is directed to the rotary kiln, where it nourishes fuel combustion. The fairly coarse dust collected from clinker coolers comprises of cement minerals and is restored to the operation. Based on the cooling efficiency and desired cooled temperature, the amount of air used in this cooling process is approximately 1-2 kg/kg of clinker. The amount of gas to be cleaned following the cooling process is decreased when a portion of the gas is used for other processes, such as coal drying. Electricity consumption of the modern grate cooler ranges from 4 to 8 kWh/t of clinker. The economic lifetime is estimated at more than 10 years.

Figure 3:

Figure -3 Clinker produced and transported

Clinker Storage

Although clinker storage capacity is based on the state of the market, a plant can normally store 5 - 25% of its annual clinker production capacity. Equipment such as conveyors and bucket elevators is used to transfer the clinkers from coolers to storage areas and to the finish mill. Gravity drops and transfer points are typically vented to dust collectors.

Figure 4: Production and transportation of clinker

Finish Milling

During the final stage of Portland cement production, known as finish milling, the clinker is ground with other materials (which impart special characteristics to the finished product) into a fine powder. Up to 5% gypsum and/or natural anhydrite is added to regulate the setting time of the cement. Other chemicals, such as those that regulate flowability or air entrainment, may also be added. Many plants use a roll crusher to achieve a preliminary size reduction of the clinker and gypsum. These materials are then sent through ball or tube mills (rotating, horizontal steel cylinders containing steel alloy balls), which perform the remaining grinding. The grinding process occurs in a closed system with an air separator that divides the cement particles according to size. Material that has not been completely ground is sent through the system again.

Packing and Loading

Once the production of Portland cement is complete, the finished product is transferred using bucket elevators and conveyors to large storage silos in the shipping department. Most of the Portland cement is transported in bulk by railway, truck, or barge, or in 43 kg multi-walled paper bags. Bags are used primarily to package masonry cement. Once the cement leaves the plant, distribution terminals are sometimes used as an intermediary holding location prior to customer distribution. The same types of conveyor systems used at the plant are used to load cement at distribution terminals [Jones R., 1993].

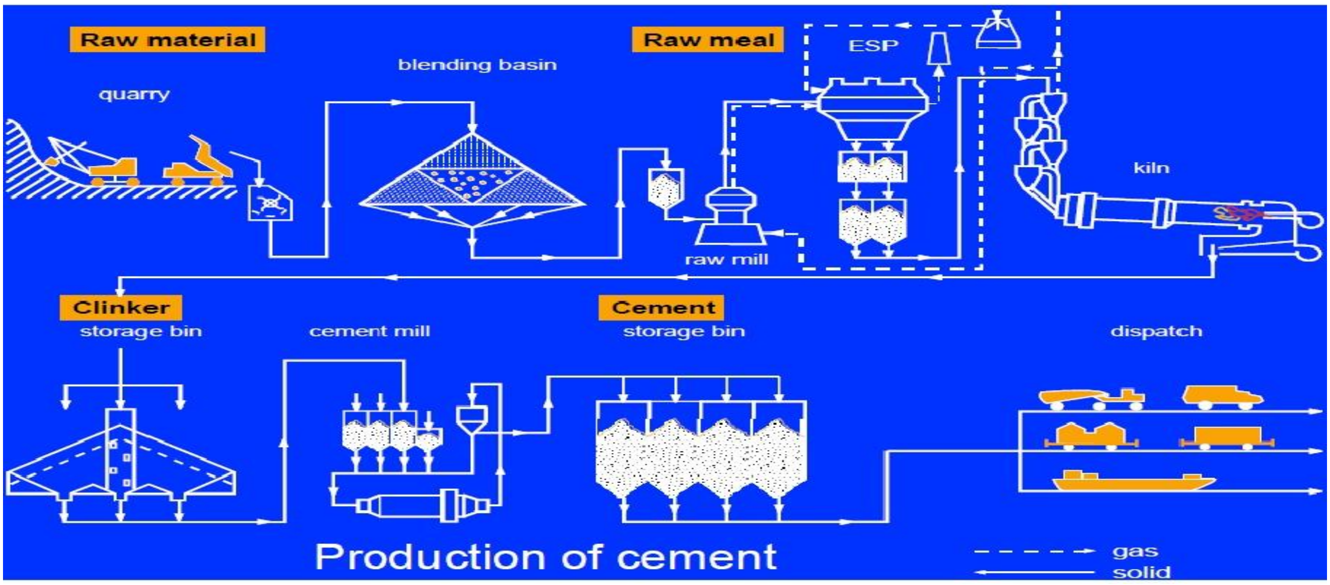


Figure 5: Schematic diagram for cement production

Clinker Storage

To allow for necessary operational flexibility, a cement plant is usually able to store from 5% to 25% of its annual clinker production capacity. The storage requirement largely depends on the shipping cycle. Northern plants usually manufacture and store clinker during the inactive winter months for grinding during the summer shipping season.

Cement Milling

Emissions of PM from mill vents, air separator vents, and material-handling system vents constitute the air pollution concerns in the finish mill department. About 30%–40% of the particles of ordinary Type I Portland cement are finer than 10 µm. For Type III, high-early-strength Portland cement, the percentage of particles finer than 10 µm increases to the 45%–65% range. Typically, about 90% of cement will pass a 325-mesh (44-µm) sieve. The potential air pollution problems associated with the manufacture, handling, and transportation of cement have their origin in the large proportion of very fine particles in the product.

2.6. Quality control of raw material

This is ensured by analyzing the chemical composition of the raw materials.

Table 1 Attainable Raw Material Quality

Raw material	Oxides	Attainable composition
Limestone	CaO	48.5 - 52%
	Al_2O_3	1.6% - 2.9%
Shale	SiO_2	24 - 40%
	Al_2O_3	6 - 15%
Silica sand	SiO_2	70 – 80%
Iron	Fe_2O_3	40% and above
Gypsum	SO_3	38 - 48%
Pozzolana	Al_2O_3,SiO_2, Fe_2O_3s	70% and above

Basically quality of cement is improved and attained from the scratch of the process, i.e., from mining of the raw material. This is done by communicating geologist with the laboratory staff in the time of transportation from the quarry site to the crusher and storage. For instance, for the high-grade and low-grade limestone, it may be above and below the standard in the raw material storage.

Energy

The energy used by the cement industry is estimated at 2% of the global energy consumption; 5% of global manmade carbon dioxide emissions originate from cement production. The general characteristics of the imported coal considered for initial design purposes are given below.

Table 2. The General characteristics of the imported coal considered for the initial design purpose

No.	Specification Parameters	Value/Range(%)
1.	Total moisture content as received	10- 15 %
2.	Inherent moisture air dry (Maximum)	3.5%
3.	Ash content (Dry)(Maximum)	17.0%
4.	Volatile matter	24.0 – 30.0%
5.	Gross calorific value (received) (Minimum)	6200 kcal/kg
6.	Net calorific value (received) (Minimum)	6000 kcal/kg
7.	Sulfur content (Maximum)	1.0%
8.	Grain size range	0.0 – 50.0mm, Max: 300mm
9.	Angle of repose	40°
10	Bulk density (t/m^3)	0.72 -0.88

Table 3. Emission Limits of Ethiopia for Cement Manufacturing

Items	Unit	Range	Pollutant media
PM	Mg/Nm^3	>30	Air, Geosphere, person
CO	%	<3	Air, Person
CO_2	Ton	44%	Air, Geosphere, person
NO_x	PPM	200-250	Air,
SO_2	%	0.5-1	Air
O_2	%	3-4	Air, Energy

Emission at Quarries

Quarries at cement plants are like other crushed stone quarries. The necessary operations include rock drilling, blasting, excavation, loading, hauling, crushing, screening, materials handling, stockpiling, and storing. There are many different operating methods, types of equipment, and equipment brands that are used to accomplish these tasks. The primary air pollutant associated with open-faced quarry operations is PM.

2.8. Emission at raw material feeders, stackers, blenders, reclaimers, and mills

The raw material feeders, stackers, blenders, and reclaimers used to combine the raw materials can produce fugitive PM emissions. Transfer points on belt conveyor systems and bucket elevators that serve to transport raw materials from storage to the raw mill department can also generate fugitive PM emissions. There are no particulate emissions from the wet grinding process, except for the materials-handling systems ahead of the mills. Dry raw mills and their auxiliary equipment are all designed to run under negative pressure to suppress PM emissions. Nevertheless, poorly designed or maintained seals and closures throughout the system can result in fugitive PM emissions. If these systems experience positive pressure through a fan failure or other cause, short-term PM emissions can be expected until the system can be shut down. During colder weather, the vents from dryers, raw mills, and air separators may exhibit a steam plume that is sometimes confused with PM emissions. The condensate will dissipate within a few meters of the emission point. Fabric filters in the vent circuits for dryers, raw mills, and air separators must be insulated to prevent internal moisture condensation and the resultant blinding of bags [Fistum Consultancy service, 2008].

Emission at Pyroprocess

The historic gaseous pollutants of concern from cement kilns are the oxides of nitrogen (NO_X), sulfur dioxide (SO_2), and carbon monoxide (CO). The emissions of CO2are of increasing interest because of concerns about global climate change. In whole or in part, these emissions from cement kiln systems are the products of combustion and/or high-temperature processes. “The principal gaseous emissions from the Pyroprocessing system in a typical descending order by volume are nitrogen, CO_2, water, oxygen, NO_X, SO_2, CO, and hydrocarbons. The volumetric composition range of these constituents is from about 73 percent to less than 10 ppm”. Emissions of acid gases (AGs), ammonia (NH3), and dioxins and furans (D/Fs) are also of current interest (F.L. Smidth & Co. As).

Sulfur dioxide

Sulfur dioxide results from the oxidation of sulfide or elemental sulfur contained in the fuel during combustion. In addition, sulfide or elemental sulfur contained in raw materials may be “roasted” or oxidized to SO_2 in areas of the Pyroprocessing system where sufficient oxygen is present and the material temperature is in the range of 300 °C–600 °C (IPCC, 2005).

Carbon Monoxide

CO is a product of incomplete combustion (PIC) of carbonaceous fuels resulting from insufficient oxygen at the combustion site, insufficient mixing of oxygen and fuel at the combustion site, and/or rapid cooling of the combustion products to below the ignition temperature of CO before its complete oxidation. CO can be formed unintentionally at any of the combustion sites in the Pyroprocessing system. The emission of CO usually represents partially burned and underutilized fuel. However, because of using oxygen-deficient combustion in the riser duct or Calciner as a NO_X control strategy.

Carbon Dioxide

Carbon dioxide results from the combustion of carbonaceous fuel and the Calcination (decarbonization) of the calcareous component of the raw material mix, an essentially unavoidable and fixed consequence of cement manufacture. Of the total amount of CO_2 emitted from a cement kiln, about half of the CO_2 originates from the raw material, while the other half originates from the combustion process. There is about one ton of CO_2 emitted per ton of clinker produced. More thermally efficient systems emit slightly less than one ton, while less thermally efficient systems emit slightly more than one ton.

Particulate Matter emissions

PM emissions associated with intermediate and final materials handling and storage (including crushing and grinding of raw materials); handling and storage of solid fuels; transportation of materials (e.g., by trucks or conveyor belts), and bagging activities. The recommended pollution prevention and control techniques include the following:

- Use of a simple, linear layout for materials handling operations to reduce the need for multiple transfer points;
- Use of enclosed belt conveyors for materials transportation and emission controls at transfer points;
- Cleaning of return belts in the conveyor belt systems;
- Storage of crushed and preblended raw materials in covered or closed bays;
- Storage of pulverized coal and petroleum coke (pet–coke) in a silo.

2.9. Air Emission Characteristics in Cement Plants

Cement manufacturing facilities are recognized as major stationary sources of air pollutants due to the high-temperature chemical reactions and extensive material handling involved throughout the production process. Emissions are generally categorized into **gaseous pollutants** and **particulate matter (PM)**, both of which pose significant threats to environmental and human health if left uncontrolled.

2.9.1. Gaseous Emissions

Among the gaseous pollutants, **CO_2** is the most abundant emission from cement plants. It is released from two primary sources: the **calcination of limestone** ($CaCO_3$), which decomposes into calcium oxide and CO_2 at high temperatures, and the **combustion of fossil fuels** such as coal and petcoke used to heat rotary kilns. According to the emission data from Messebo Cement Factory, approximately 0.52 tonnes of CO_2 are emitted per tonne of clinker produced, with total quarterly emissions exceeding 500,000 tonnes during peak production years (MCF, 2016–2017 data, Appendix 3).

Nitrogen oxides (NO_x) are another major pollutant formed during pyroprocessing. These gases are primarily generated through **thermal oxidation of atmospheric nitrogen**, which occurs when combustion temperatures exceed 1,300 °C—conditions typical in cement kilns. NO_x formation is influenced by burner design, flame temperature, excess air levels, and residence time (Miller & Bowman, 1989). High NO_x emissions contribute to smog formation and respiratory problems in humans, and controlling them requires specialized technologies such as low-NOX burners, staged combustion, or selective non-catalytic reduction (SNCR) systems.

Sulfur dioxide (SO_2) emissions originate both from sulfur content in raw materials and from the oxidation of sulfur-bearing fuels during combustion. The extent of SO_2 release depends on kiln operating conditions and the availability of alkalis in the raw mix that can capture sulfur compounds. In precalciner kilns with optimized sulfur absorption, SO_2 emissions can be substantially reduced; however, in systems with oxygen-deficient zones or poor fuel mixing, sulfur compounds may escape as gaseous emissions (Greer, 2003). CO, on the other hand, is typically released due to incomplete combustion of fuels, especially under conditions of low oxygen availability or poor burner performance. Although CO is not as long-lived as CO_2, it serves as an indicator of combustion efficiency and can lead to local oxygen displacement and toxicity risks.

2.9.2. Particulate Matter (PM)

Particulate matter emissions in cement plants are largely generated during crushing, raw material grinding, clinker handling, finish milling, and material transfer operations. These emissions are composed of fine mineral dust, kiln ash, and sometimes trace metals, depending on the raw mix. The particle size ranges from visible coarse dust to respirable fine particles under 10 microns (PM_{10}), which can penetrate deep into the respiratory system and cause significant health issues. Particularly in the Messebo Cement Factory, PM emissions were reported during the raw material preparation and clinker processing stages, with recorded concentrations exceeding recommended limits in some areas (Appendix 1–3).

Fugitive dust is often released at conveyor transfer points, belt feeders, and silo discharges if enclosures and dust collectors are not properly maintained. While fabric filters and baghouse systems are commonly used to control PM emissions, their efficiency depends on maintenance practices and system design. According to the study, bag filters in MCF achieved removal efficiencies close to 99.95% under optimal operating conditions, yet localized dust emissions persisted due to uncovered transport systems and inconsistent maintenance.

2.10. Existing Emission Control Techniques in Cement Manufacturing

Emission Control at quarries

Control measures for PM emissions in quarries include water sprays with and without surfactants, foams, chemical dust suppressants, wind screens, equipment enclosures, paving, mechanical collectors, and fabric filters on operating equipment, and material storage buildings, enclosures, bins, and silos with and without exhaust venting to fabric filters. Collected dust is returned to the process. Raw materials obtained from off-site locations, including coal or petroleum coke used for fuel, can also generate particulate emissions as a result of vehicle loading and unloading, material handling, stockpiling, and haulage.

Emission Control at raw material feeders, stackers, blenders, reclaimers, and mills

Dust collecting devices in the raw mill and raw mix storage areas include mechanical cyclones, fabric filters, and, rarely, electrostatic precipitators (ESPs). When employed, mechanical collectors are often used in series with one of the other, more efficient dust collection devices. The collected dust is returned to the mill system or raw material stream. Vertical raw mills are most often closely coupled to the pyro processing system. The air pollution control measures for these mills will be found in the following section on Pyroprocessing.

Emission Control at Pyroprocess

The following discussion describes some of the existing and potential technologies available for the control of the primary air emissions presented above. Included in the discussion are the synergetic and counteractive effects that these various technologies will have on these gaseous pollutants, detached plumes, and waste disposal (Greer, 2003). A “synergetic” effect would be expected to decrease the generation or emission of other pollutants, and a “counteractive” effect would be expected to degrade environmental performance or product quality.

Table 4. Potential Control Technologies for Gaseous Pollutants in Cement Manufacturing

Existing control technologies		Pollutant for which technology was intended
Oxygen / excess air control	Increase	SO2, THC, CO
	Decrease	NOX
Fuel substitution (lower sulfur)		SO2
Pyroprocessing system design		SO2
Low-NOX burner and low-NOX calciner		NOX
Process improvements		NOX
Process control improvements		NOX
Staged combustion		NOX
Pyroprocessing system design		THC, CO
Good combustion practice		CO
Fabric filter absorption		SO2

Oxygen/Excess Air Control (Increase)

To provide for maximum thermal efficiency, the oxygen concentration in the flue gas at the feed end of a rotary kiln and/or the exit of the preheater tower normally is normally held as close as possible to 1%. This oxygen concentration may be insufficient to allow for complete combustion, and CO could be generated at the combustion site. A slight increase in the amount of air passing through the kiln system is often adequate to reduce the excess emissions of organic compounds and CO, and to oxidize sulfur, originating in the fuel, to a solid sulfate that is retained in the clinker or expelled from the system with the CKD. An increase in oxygen at the combustion site tends to increase thermal and/or fuel NO_X. Additional fuel is required to heat the excess air to combustion temperatures and resulting in a slight increase in CO_2 emissions. If there are localized reducing conditions in the kiln because of flame impingement or other causes, the increase in oxygen may not reduce SO_2 emissions, but NO_X emissions may increase. Because of the inherently high removal efficiency for fuel-based SO_2 in a Calciner, oxygen control at this combustion site would not be expected to improve SO_2 removal in Precalciner systems.

Oxygen/Excess Air Control (Decrease)

For control of NO_X originating at the high-temperature combustion site in a rotary kiln, a decrease in oxygen (excess air) in the burning zone tends to minimize the generation of thermal and fuel NO_X. Both mechanisms of NO_X formation are oxygen-dependent. The reduction in excess air reduces the strength of the oxidizing conditions in the rotary kiln and usually causes an increase in SO_2 generated from the fuel used in the main flame. If there is flame impingement on the material in the kiln, *i.e.*, localized reducing conditions, the decrease in oxygen concentration may further exacerbate SO_2 generation. The reduction of oxygen concentration at the primary combustion sites in a Precalciner kiln system will also tend to reduce the generation of fuel NO_X. The decrease in oxygen concentration at combustion sites may cause or increase the generation of CO. There is a small energy benefit for reducing excess air in the system that will result in a slight decrease in fuel consumption and CO_2 emissions. The production of cement clinker under generalized or localized reducing conditions usually has deleterious effects on product color and performance.

Fuel Substitution (Lower Total Sulfur)

In Precalciner kiln systems, the emission of SO_2 that originates in the fuel is often nil because of the inherent ability of the Calciner and an alkali-bypass equipped kiln to absorb and/or remove sulfur. It is intuitive that a reduction in the sulfur content of a solid fuel or the change to a sulfur-free fuel, e.g., natural gas, has the potential to reduce SO_2 emissions. Because of the complexities of the cement pyroprocess, a change in the sulfur content of the fuel does not always result in expected changes in SO_2 emissions. Whenever a fuel is changed, there may be unintended effects on the process and the resulting pollutants. For example, the replacement of coal with natural gas in a long-dry kiln system to reduce SO_2 emissions will increase NO_X emissions. Because energy costs nominally represent about one-third of the cost of cement manufacture, fuel substitution at a particular plant may not be economically viable.

Pyro Processing System Design

Unique kiln systems of atypical design can take advantage of the inherent properties of the cement manufacturing process to achieve environmental goals under site-specific circumstances. These systems often must use additional energy or suffer a lower production rate than traditional designs, but the improved environmental performance and the avoidance of problems associated with pollution abatement equipment occasionally make such designs acceptable to an owner. At one plant, there is a unique combination of a low-calciner, a single-stage preheater, and a dryer crusher that exceeded all environmental and production expectations, including very low emissions of SO_2. In this case, fuel consumption with the attendant NO_X and CO_2 emissions was higher than would have been experienced with a traditional Precalciner kiln system.

Low-NOX Burner

Several vendors provide adjustable burners with proprietary designs that are intended to reduce NO_X generation through the mixing scheme for fuel and primary air by reducing flame temperature, altering turbulence in the flame, and establishing oxygen-deficient recirculation zones in the flame. While these burners have the capacity to alter the flame velocity and shape for process purposes, they have met with mixed success in the documented control of NO_X generation. Most often, these burners are installed with an indirect-fired coal system as part of a retrofit project for a direct-fired system or as part of a new Pyro-processing system. At the conclusion of a successful project, it is impossible to sort out the relative contributions of the NO_X burner and the indirect-fired coal system to the reduction of NO_X generation.

Low-NOX Calciner

All vendors of cement Pyro-processing systems offer proprietary Calciner designs that carefully control the mixing sequence of fuel, air, and raw materials in the Calciner vessel. The common feature of all these systems is an oxygen-deficient initial combustion zone in which free radicals are generated that subsequently react with NO_X to form molecular nitrogen and other reaction products (Miller and Bowman, 1989). At the operating conditions found in the Calciner, CO is also formed. The initial combustion zone is followed in the gas flow path by a secondary combustion zone in which residual CO in the flue gas is oxidized to CO_2. These designs have worked quite well in new installations. When applied to Calciner replacement or retrofit projects, physical restraints often limit the ability of the vendor to install a fully functional low-NO_X Calciner. The result may be an unpredictable and disappointing reduction in NO_X generation in the Calciner. In all these designs, there is the possibility of increased emissions of residual CO if the downstream oxidation is not complete

Process Improvements

Because of the reduced consumption of fuel per unit of production, almost any improvement in an existing kiln system that improves the thermal efficiency of the process will be accompanied by a reduction in long-term NO_X emissions per ton of clinker. To help justify the associated capital expenditures, many process improvement projects also result in increased production that tends to negate decreases in overall NO_X emissions. When compared to a steam boiler or power plant, the high variability of NO_X emissions from a properly operated cement kiln is well known. Process improvements that serve to make the kiln operation more stable without necessarily increasing production also accomplish NO_X reductions over the short term, the long term, and per ton of clinker. Any process improvement project should be evaluated for its effect on the generation and emission of all pollutants.

Process Control Improvements

Process control improvements are characterized by the installation of new or better instrumentation and/or process control systems. In older kiln systems, the improvement might mean replacing an analog process control system with a digital computer. In newer kiln systems with an adequate digital computer, the use of one of the expert or fuzzy logic control systems and the necessary process instrumentation could represent a significant process control improvement. In essence, the expert systems are satellite computers that guide the process computer in controlling the kiln system. They can detect subtle changes in the process and to take corrective actions of the appropriate magnitude more rapidly than the central control room operator. The common purposes of most process control improvements on kiln systems are to improve thermal efficiency and the clinker production rate. However, if a process control improvement project simply results in a more stable Pyroprocessing system, lower NO_X emissions over the short term and the long term, per ton of clinker will result. Any process control improvement project should be evaluated for its overall effect on the process and on the generation and emission of all pollutants.

Staged Combustion

The function of staged combustion (sometimes called secondary firing) in preheater or Precalciner kiln systems is to develop a reducing zone in the flue gas flow path after the burning zone in which free radicals produced during staged combustion of hydrocarbon fuels react with NO_X from the burning zone to form molecular nitrogen and other reaction products. The most prevalent location for staged combustion is in the riser duct between the discharge of the rotary kiln and the Calciner vessel. Typically, natural gas is the most convenient fuel, but pulverized (powdered) coal, used oil, and waste-derived fuels are also used for this purpose. Worn or rejected whole passenger car tires are also inserted into the feed end of the rotary kiln to accomplish NO_X reduction through staged combustion. In preheater kiln systems, there is a high probability of increased CO emissions unless there is a source of air (oxygen) to oxidize residual CO downstream of the staged combustion site in the flue gas flow path. In Precalciner kiln systems, the residual CO from staged combustion has an opportunity to be burned in the Calciner vessel, so the probability of increased CO emissions resulting from staged combustion is reduced but not necessarily eliminated.

Pyroprocessing System Design (CO Control)

Because the emission of CO from unburned fuel represents an economic loss, most cement Pyroprocessing systems are designed to ensure the complete combustion of fuels. In those situations where CO generation occurs simultaneously with the deliberate generation of free radicals used as reducing agents to minimize NO_X emissions, the process is normally designed to oxidize residual CO to CO_2 once the NO_X reduction has been accomplished. Each vendor of cement kiln systems has several proprietary designs intended to minimize CO emissions while accomplishing other process and pollution abatement objectives. For example, in a low-NO_X Calciner, the fuel and tertiary air are introduced appropriately to the vessel to minimize residual CO. In staged combustion, an oxidizing zone sequentially follows a combustion zone that operates in an oxygen-deficient environment.

2.11. Potential and Innovative Pollution Control Technologies

Fabric Filter Absorption

Older literature suggests that SO_2 is removed from cement kiln flue gas in a fabric filter PMCD. This removal seldom has been observed in practice because the bulk of the material on the filter, i.e., calcium carbonate, is not reactive with SO_2 at the temperature and humidity conditions in the fabric filter. If calcium oxide is present on the filter medium, e.g., in an alkali-bypass PMCD, a small but measurable reduction in SO_2 concentration in the flue gas may be observed. If a scrubbing reagent, e.g., hydrated lime, were added to the flue gas stream ahead of the PMCD, some adsorption of SO_2 might be observed.

Bag Filters Operation

The origin of dust in the cement production process in different sections, such as preparation of raw materials, raw material grinding, readiness of raw materials combination, clinker cooler, clinker storage, final milling, packing, and loading, shall be worth of consideration with dust formation. One of the important dust control devices in the cement industry is the application of fabric filters with a diameter of 300mm or less and with a height of 15m. These fabric filters are generally made from woven and needle felt of natural or artificial fibers. Fabric filters absorb soft micron particles with a considerable operation efficiency of 99.95% [9].

Bag filters are important equipment in a cement factory. In these filters flow that includes gas and dust passes through the pores in the filter material, and the is filtered by the remaining on the bag. Afterwards, due to dust increase on the bag, the filter is shaken until the collected dust leads to the exit hopper. To obtain better operation after introducing the operation mechanism, the same step as creating a good situation for maintain and maintenance and repairs, by considering important fragments and appointing a minority of stock in the stores to carry out the planning of the maintenance and repairs improvement of stockis mandatory.

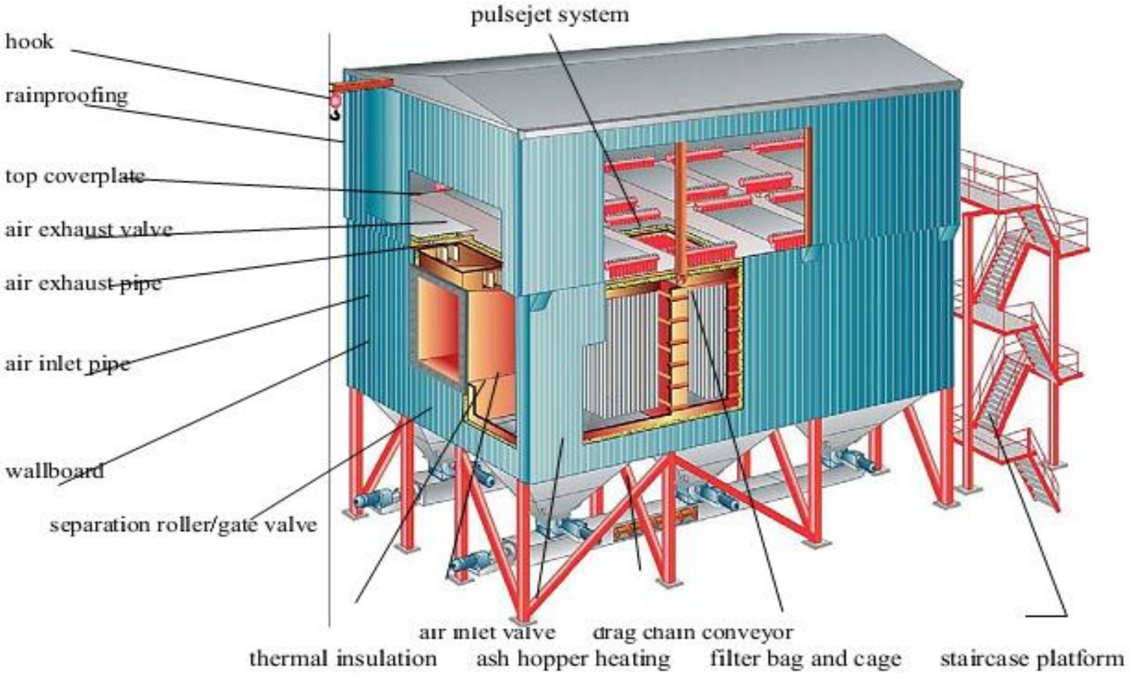


Figure 6: Baghouse filter components

The law of conservation of mass leads to what is called a mass or a material balance.

Mass In = Mass Out + Mass Stored (returned)

Raw Materials = Products + Wastes + Stored Materials.

$\Sigma mR = \Sigma mP + \Sigma\ mW + \Sigma mS$

(Where Σ (sigma) denotes the sum of all terms).

$\Sigma mR = \Sigma mR1 + \Sigma\ mR2 + \Sigma mR3$ = Total Raw Materials

$\Sigma mP = \Sigma mP1 + \Sigma\ mP2 + \Sigma mP3$ = Total Products.

$\Sigma mW = \Sigma mW1 + \Sigma\ mW2 + \Sigma mW3$ = Total Waste Products

$\Sigma mS = \Sigma mS1 + \Sigma\ mS2 + \Sigma mS3$ = Total Stored Products [23].

Table 5. Limit Values of parameters for Emission (National and international emission standards)

Pollutant	**Ethiopian Standard (mg/Nm³)**	**WHO/IFC Guideline**
Total PM	150	30–50 (depending on tech)
SO_2	1000	500
NO_x (as NO_2)	2000	800
CO (as %)	<3	

CHAPTER 3: METHODOLOGY

3.1. Description of study area

This study was conducted at MCF, one of Ethiopia’s largest cement producers, located approximately 11 km northwest of Mekelle City in the Tigray Region, Ethiopia. Geographically, the factory lies at an altitude of 2,050 m above sea level and is positioned along the Mekelle–Abi-Adi asphalt road. MCF occupies a strategically important location due to its proximity to abundant limestone and shale deposits, which are the primary raw materials for cement production. The factory operates multiple production lines and includes raw material mining, preparation, pyroprocessing, clinker cooling, cement milling, and packaging units, all of which are potential sources of air pollution.

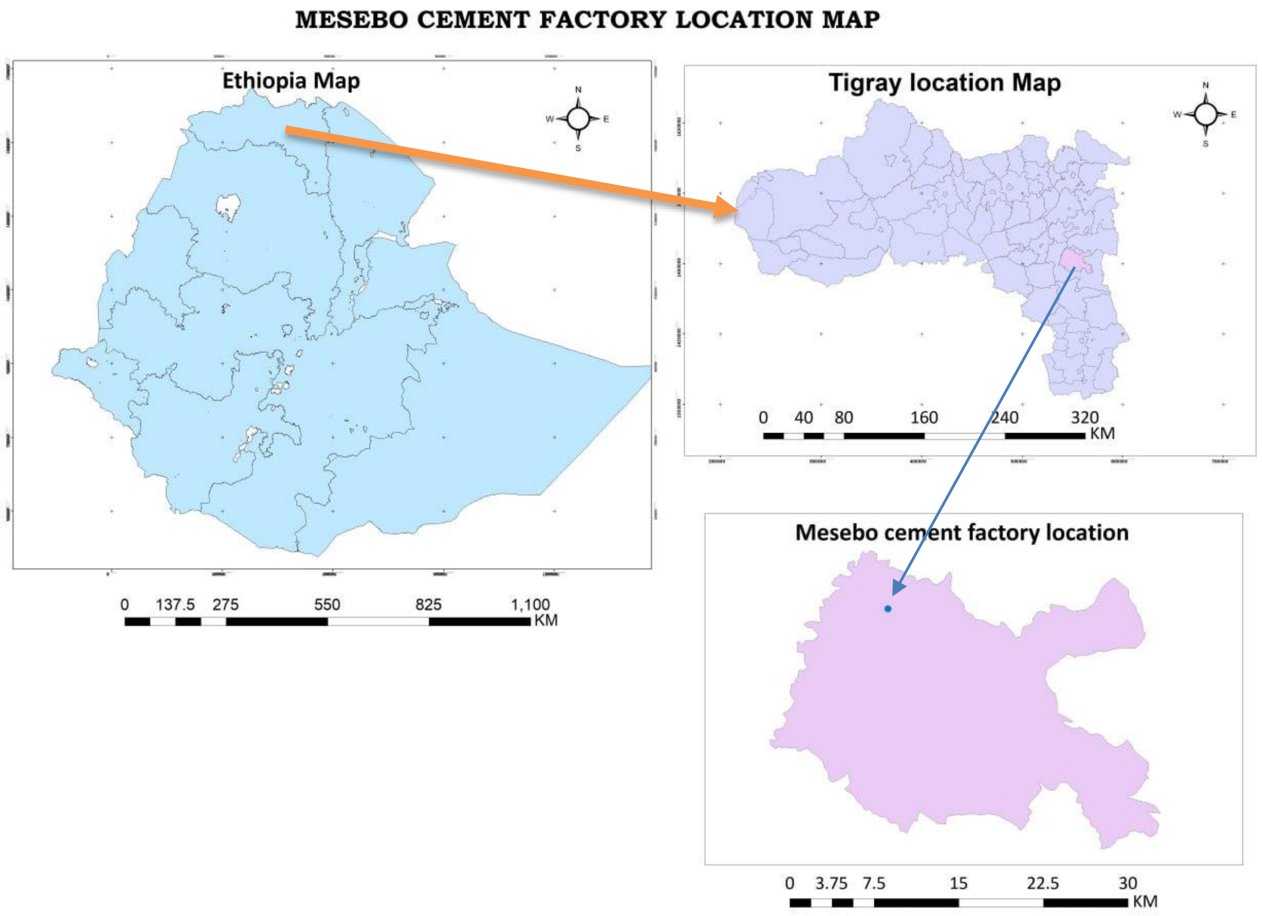


Figure 7: Satellite Map of MCF(arcGIS)

Figure 8: Picture of MCF

3.2 Samples and Data Collection and Design

A mixed-method approach integrating both quantitative and qualitative techniques was employed to ensure a comprehensive evaluation of air pollution control practices at MCF. The research design was structured into identifying major emission sources, quantifying pollutant levels at each production stage, and evaluating the effectiveness of existing pollution control technologies.

3.2.1 Primary Data Collection

Primary data collection involved direct environmental measurements, structured field observations, and stakeholder surveys. Air quality monitoring was carried out at critical emission hotspots within the factory premises, including the coal mill, raw material storage, kiln feed area, clinker cooler, and cement mill. Measurements focused on key pollutants such as CO_2, CO, SO_2, NO_x, and PM_{10}. A structured questionnaire was administered to 1,235 participants, including factory employees and residents in the vicinity, to gather perceptions on emission visibility, control effectiveness, environmental awareness, and training. This decision was based on the manageable size of the population, the high likelihood of varied exposure to air pollution across job roles, and the need for comprehensive and representative data. To ensure validity, the questionnaire underwent expert review by environmental specialists and was pilot-tested with 30 randomly selected employees. Feedback from the pilot phase led to improvements in question clarity and structure. The internal consistency of the questionnaire was assessed using Cronbach’s Alpha, which yielded a score of 0.82, indicating strong reliability.

Qualitative visual assessments were performed to identify dust accumulation, visible emissions, and the condition of filtration and enclosure systems.

3.2.2 Secondary Data Collection

Secondary data was collected from internal factory records, government regulatory reports, and published scientific literature. This included: daily production reports (DPR), clinker and cement output data from 2000 to 2017, historical emission logs, environmental impact reports, and national and international emission standards (e.g., WHO, IFC, FDRE EPA). This dual approach enabled longitudinal analysis of emission trends and helped contextualize primary measurement results within broader regulatory and industrial frameworks.

3.3. Data Collected

The data collected for this study were systematically categorized into five principal components to ensure comprehensive assessment of the plant's environmental performance. Gaseous emissions, including CO_2, CO, SO_2, and NO_x, were measured at selected production stages using a calibrated Yuante multi-gas detector to determine the concentration levels of key atmospheric pollutants. Ambient dust concentrations were monitored employing TM Data (Sk-version) devices, with specific attention given to both fine and coarse particulate matter (PM) fractions to evaluate airborne dust dispersion.

Standard industrial temperature sensors and digital sound level meters were utilized to record thermal and acoustic conditions throughout major operational phases. Furthermore, structured survey questionnaires were administered to gather data on workers' and nearby community perceptions concerning the effectiveness of emission control measures, dust visibility, community health impacts, and the adequacy of environmental training programs.

In addition to field measurements and survey data, secondary information was obtained from plant operational records, including historical clinker production volumes, cement type distributions (OPC, PPC, and PLC), fuel types and consumption rates, and the emission control systems currently in operation. These combined datasets provided a robust foundation for analyzing the environmental conditions and management practices at Messebo Cement Factory.

3.4 Data Analysis

3.4.1 Quantitative Analysis

In the quantitative analysis phase, environmental monitoring data collected from MSF were processed using both descriptive and inferential statistical methods to ensure accurate interpretation. Continuous gas concentration profiling and emission trend analysis were conducted using the FLS Airloq A/S Gas Analyzer, which enabled high-resolution monitoring of gaseous pollutants over time. In parallel, the SDR computer system was employed to record real-time data for key emissions, including CO_2, NO_x, SO_2, and CO, across various production units. These measured values were systematically compared with both national standards set by the FDRE EPA and international benchmarks from the WHO and IFC to assess regulatory compliance. Furthermore, emissions data were subjected to detailed analysis using the Intergovernmental Panel on Climate Change (IPCC) Tier 1 and Tier 2 methodologies, enabling the estimation of total CO_2 emissions attributable to clinker production and calcined cement kiln dust (CKD). The CO_2 emission factor was calculated based on the proportion of clinker content in cement, CaO concentration in raw materials, and the thermal characteristics of the raw meal combustion process.

3.4.2 Qualitative Analysis

Data from surveys and field observations were thematically analyzed to identify behavioral patterns, systemic gaps, and stakeholder concerns regarding emission control. Observational notes were used to corroborate quantitative findings, especially in cases of visible dust plumes and unsealed transport systems. Photographic documentation, anecdotal worker feedback, and expert interviews with factory engineers and environmental officers were synthesized to draw meaningful interpretations about operational efficiency and technological limitations.

3.5 Quality Assurance and Calibration

All instruments used in this study were calibrated according to manufacturer guidelines before deployment. Routine checks and recalibrations were performed to ensure data integrity and minimize instrumental error. Environmental readings were taken multiple times at each site to account for temporal variations and ensure reproducibility.

Table 6. Parameters measured and instruments used

Parameter	**Instrument Used**
CO_2, CO, SO_2, NO_x (Gases)	Yuante Gas Detector
Dust/Particulate Matter	TM Data (Sk-version)
Noise Levels	Digital Sound Meter
Temperature	Standard Industrial Sensors

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Results

4.1.1 Survey result on Emission Control Effectiveness, Air Quality Perception, and Community Awareness

Table 7 summarizes respondents' views on dust visibility, emission control effectiveness, emission frequency, perceived improvements, preferred mitigation measures, environmental training, and community awareness regarding air pollution at MCF. Approximately 65% of respondents frequently observe visible dust or emissions, indicating that particulate pollution is a widespread and persistent issue in the area. Only 7% reported rarely or never noticing emissions. Similarly, around 65% perceive current dust control measures as ineffective, with only 35% considering them somewhat effective. In terms of progress, over half of the respondents saw little to no improvement in air pollution control, while only 36% acknowledged some improvement, including a small portion (16%) who noted significant progress. This variation may relate to respondents' proximity to the emission source, with those farther away perceiving greater change.

Regarding preferred solutions, water spraying (32%) and upgraded filtration systems (24%) were identified as the most effective control methods, followed by material covering (20%). In contrast, softer approaches like planting vegetation (12%) and equipment maintenance (8%) were seen as less impactful, highlighting a preference for visible and immediate control measures. A notable gap was found in environmental training: 76% of respondents had received no training, suggesting limited awareness-building efforts. This aligns with findings on community awareness—over half of the respondents perceived public understanding of air pollution issues as low, with only 12% rating it as high.

Table 7 Summary respondents' on emissions at MCF

Item	Option	Number of Responses	Percentage (%)
Do you observe visible dust or emissions from the MCF facility?"	Yes	800	65
	No	350	28
	Not Sure	85	7
How effective do you find the current dust and emission control measures at MCF?	Very effective	100	8
	Moderately effective	335	27
	Not effective	800	65
How often do you witness dust or smoke emissions from MCF's operations?	Frequently	800	65
	Occasionally	250	20
	Rarely	150	12
	Never	35	3
In your view, has air pollution control at MCF improved in recent years?	Significant improvement	200	16
	Moderate improvements	500	40
	No improvements	500	40
	Not Sure	35	3
Which dust/emission control measure do you believe is the most effective for MCF to use?	Regular water spraying of roads & work areas	400	32
	Upgrading or installing advanced filtration systems	300	24
	Covering transport and storage (enclosures)	250	20
	Planting trees/vegetation as a buffer	150	12
	Improved maintenance and housekeeping	135	11
Have you ever received training in environmental management or dust/emission control practices related to MCF?	Yes	300	24
	No	935	76
How would you rate the general community's awareness of air pollution and dust issues related to MCF's operations?	High awareness	150	12
	Moderate awareness	400	32
	Very low/Not aware at all	650	53
	Not Sure	35	3

The findings from both the questionnaire responses and field observations at MCF consistently indicate that dust pollution is a serious and ongoing issue. This aligns with field observations, which revealed extensive airborne dust across various stages of production—from raw material extraction to final product handling. Observations showed dust accumulation on plant equipment, nearby buildings, and vegetation, clearly indicating the inefficiency or absence of proper dust management systems. Although 36% of respondents acknowledged some improvement in pollution control, only a small percentage (16%) reported significant progress. This could be attributed to geographic differences in exposure; those farther from the emission source may perceive relative improvements, while those closer remain heavily affected. The questionnaire responses, supported by the researcher's physical observations within the factory premises, indicate that the existing environmental control measures are either inadequately implemented or insufficient in scale to effectively mitigate emissions and workplace exposure risks.The persistent presence of visible dust plumes and uncovered raw materials indicates insufficient investment in advanced emission control technologies, such as baghouse filtration units and material enclosure systems. Furthermore, the absence of adequate environmental education and awareness programs limits proactive behavior among workers and nearby communities, thereby perpetuating unsafe operational and handling practices.

Figure 9: Observation of surrounding processes at MCF during the research study

4.1.2. CO_2 emission Analysis

The data in Table 6, from 2001 to 2017, demonstrates a consistent upward trend in clinker production and corresponding CO_2 emissions at MCF. Over this period, CO_2 emissions rose from approximately 78,884 tonnes in 2000/01 to a peak of 990,767 tonnes in 2015/16, reflecting the factory's increasing production capacity and demand. This steady growth parallels a similar rise in raw mill consumption, which expanded from 197,210 tonnes to nearly 2.48 million tonnes over the same period. The sharpest increases in both clinker output and CO_2 emissions occurred between 2012/13 and 2015/16, indicating significant production scale-up during these years. The highest annual CO_2 emission was recorded in 2015/16, closely followed by 2014/15, aligning with the highest clinker production volumes of over 1.5 million tonnes. A slight decline was observed in 2016/17, possibly due to operational adjustments or capacity limitations.

Table 8 The CO_2 emission of MCF from 2001-2017

Year	**Clinker production, tonnes**	**CO_2 emission, tonnes**	**Raw mill, tonnes**
2000-01	123,256	78,883.84	197,209.6
2001-02	184,672	118,190.08	295,475.2
2002-03	318,387	203,767.68	509,419.2
2003-04	326,123	208,718.72	521,796.8
2004-05	564,875	361,520	903,800
2005-06	616,184	394,357.76	985,894.4
2006-07	642,657	411,300.48	1,028,251.2
2007-08	707,219	452,620.16	1,131,550.4
2008-09	621,699	397,887.36	994,718.4
2009-10	489,492	313,274.88	783,187.2
2010-11	680,932	435,796.48	1,089,491.2
2011-12	679,932.3	435,156.67	1,087,891.7
2012-13	890,816.5	570,122.56	1,425,306.4
2013-14	1,090,188.9	697,720.9	1,744,302.3
2014-15	1,533,088.8	981,176.85	2,452,942.1
2015-16	1,548,073	990,766.72	2,476,916.8
2016-17	1,120,337	717,015.68	1,792,539.2

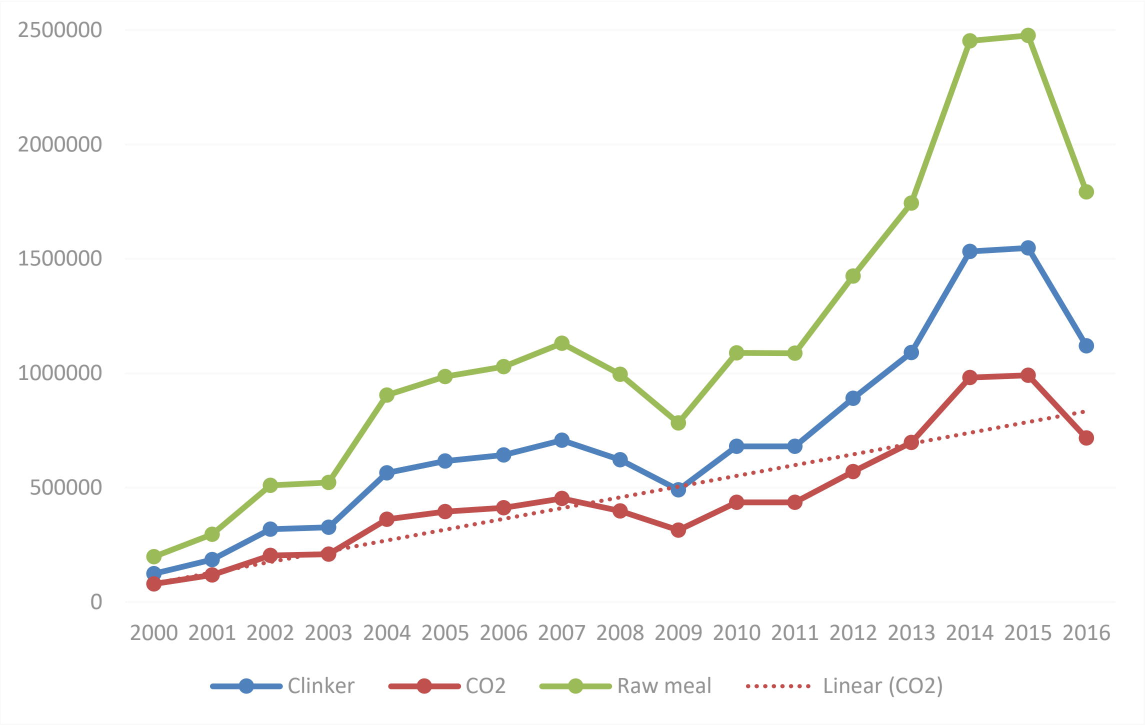


Figure 10: CO_2 emission trend at different cement Production of MCF

4.1.3. Air Pollution in Various Production Stages

Air quality measurements were conducted using a Yuante gas detector (see Appendix 1) to assess the concentration of various pollutants in the surrounding environment of key operational areas within MCF. These areas included the coal mill, coal storage, material storage, raw mill, cooler, and kiln. Measurements were taken during the entire study period to evaluate the levels of gaseous emissions (CO_2, CO, SO_2, and NOx) and particulate matter (PM) released into the atmosphere. The results of the air quality assessment are presented in Tables 9-14, which detail the measured concentrations of major pollutants, including CO_2, CO, SO_2, NO_x, and PM. These measured values were then compared against the permissible emission limits outlined in Table 5 to determine compliance with environmental standards.

4. 1.3.1. Acquisition of raw materials

The ambient air pollution data collected from MCF during raw material acquisition reveal notable variations in CO_2 concentrations, PM, and the limited presence of other pollutants across three key locations: the coal mill, coal storage, and material storage areas (Table 9). At the coal mill, CO_2 levels remained relatively stable, ranging from 350 to 360 ppm in January and February, with a slight decrease to 356 ppm in March, accompanied by a marginal drop in CO_2 volume. No detectable levels of CO, SO_2, NO_x, or PM were recorded at this site. In the coal storage area, CO_2 concentrations increased from 359 ppm in January to 490 ppm in March, with a significant peak in February (389 ppm) accompanied by a detectable CO level, indicating possible incomplete combustion or leakage. The gradual reduction in oxygen levels suggests a rise in combustion-related activity. At the material storage site, the highest CO_2 concentration was recorded in January (416 ppm), with declining values through March. This location was also the only site where SO_2 (0.16%) and particulate matter (PM) were detected, with PM levels progressively increasing from 0.64 mg/m^3 in January to 1.77 mg/m^3 in March, signaling a buildup of airborne dust and pollutant accumulation in this area. Overall, the results highlight material storage as a key hotspot for air quality concerns due to its elevated gas and particulate emissions, suggesting the need for targeted dust and gas mitigation strategies in that zone.

Table 9 Ambient air pollution levels during raw material acquisition at MCF

SN	**Site**	**GPS X**	**GPS Y**	**Elevation (m)**	**Month**	**CO_2 (ppm)**	**CO (ppm)**	**SO_2 (%)**	**NO_x (ppm)**	**O_2 (% Volume)**	**PM (mg/m^3)**
1	Coal Mill	551239	1500071	11	Jan	350	–	–	–	20.93	–
					Feb	360	–	–	–	20.93	–
					Mar	356	–	–	–	19.96	–
2	Coal Storage	551149	1500201	9	Jan	359	389	–	–	20.93	–
					Feb	389	–	–	–	20.93	–
					Mar	490	–	–	–	19.92	–
3	Material Storage	551275	1500257	11	Jan	416	–	0.16	–	20.93	0.64
					Feb	371	–	–	–	20.93	1.07
					Mar	355	–	–	–	19.97	1.77

Line Graphs: Ambient Air Pollution at MCF

The following graphs illustrate ambient air pollution levels at Messebo Cement Factory (MCF) during the raw material acquisition phase. Trends in CO_2 concentrations across different sites and the progression of PM levels at the material storage site are presented.

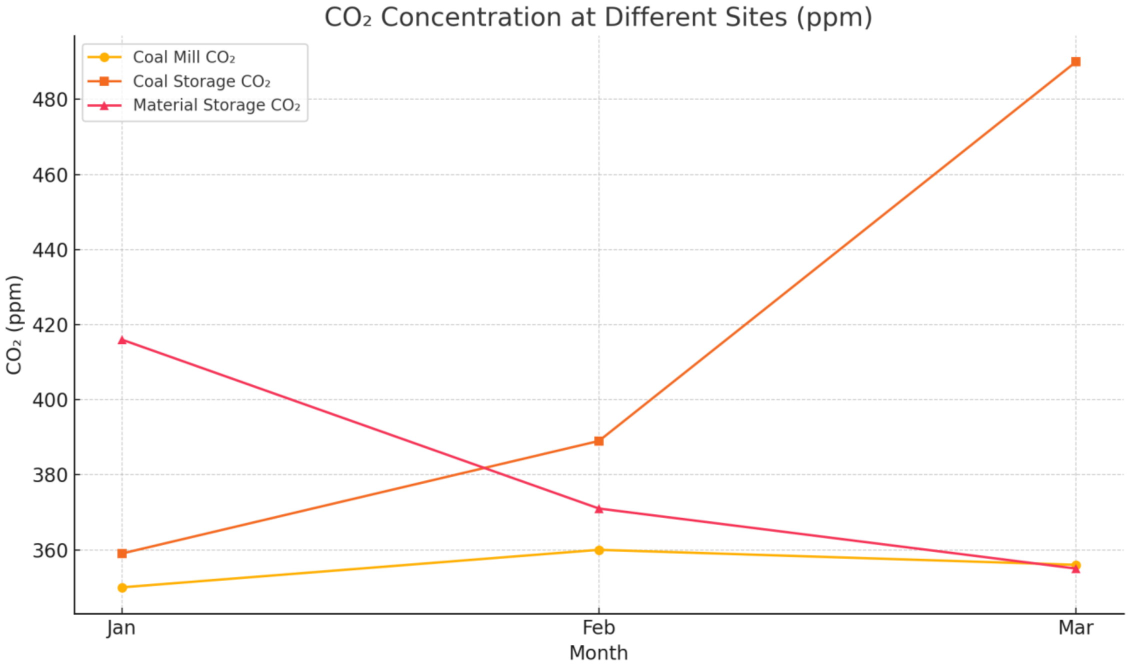


Figure 1: CO_2 concentration trends at coal mill, coal storage, and material storage sites (Jan–Mar).

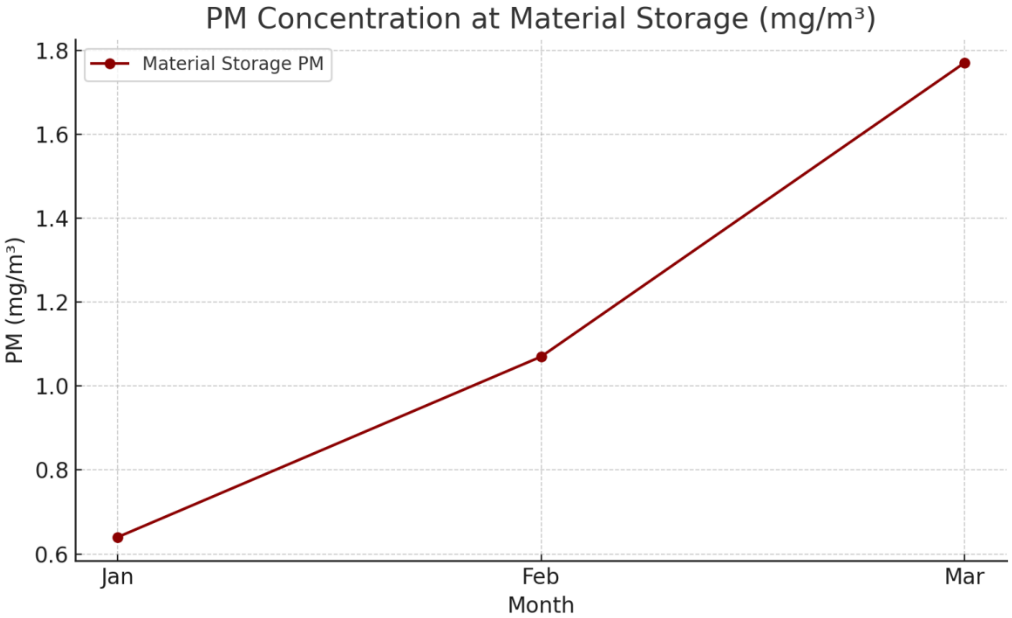


Figure 2: PM concentration trend at material storage site (Jan–Mar).

4. 1.3.2. Preparation of raw materials

The ambient air pollution data from the raw mill section of MCF shows a rising trend in CO_2 levels from January to March, increasing from 363 ppm to 401 ppm (Table 10). This suggests heightened combustion or process activity in the raw material preparation stage. Oxygen levels concurrently decreased from 20.93% to 19.94%, consistent with increased CO_2 emissions. Notably, PM concentrations remained consistently high at 94.03 mg/m³ in both January and February, with data for March unavailable. These elevated PM levels indicate persistent dust generation during the raw milling process, which could pose respiratory risks to workers and contribute to localized air quality degradation. Effective dust control measures and emission monitoring are essential to mitigate these environmental and health impacts.

Table 10. Ambient Air Pollution in Preparation of Raw Materials at MCF

SN	**Site**	**GPS X**	**GPS Y**	**Elevation (m)**	**Month**	**CO_2 (ppm)**	**CO (ppm)**	**SO_2 (%)**	**NO_x (ppm)**	**O_2 (% Volume)**	**PM (mg/m³)**
1	Raw Mill	0551132	15001457	11	Jan	363	–	–	–	20.93	94.03
					Feb	380	–	–	–	20.49	94.03
					Mar	401	–	–	–	19.94	–

4.1.3.3. Pyroprocessing (kiln feed)

The kiln and cooler sections exhibited CO_2 emissions ranging from 350 ppm to 448 ppm, with O_2 levels remaining relatively stable at around 20.93%, suggesting efficient combustion. However, the lack of data on NO_x and SO_2 levels, emissions were not consistently measured, suggesting that further investigations are required to assess combustion-related emissions.

Table 13: Ambient air Pollution in the pyro-processing of kiln feed of MCF

SN.	Messebo Site	GPS Location			Time	PPM				% Volume
		X	Y	Z		CO2	CO	SO2	NOx	O2
1	Cooler	0551272	1500009	10	Jan	360	-	-	-	20.93
					Feb	369	-	-	-	20.93
					Mar	366	-	-	-	19.96
2	Kiln	0551246	1500038	9	Jan	350	-	-	-	20.93
					Feb	422	-	-	-	20.93
					Mar	355	-	-	-	19.55
					Feb	448	-	-	-	20.93
					Mar	350	-	-	-	20.93

4.1.4. Identification of Major Air Pollution Sources

Based on a comprehensive analysis of the data collected from MCF, the following major sources of air pollution within the cement manufacturing process were identified (Table 11). These sources are categorized by operational stages and the predominant pollutants they contribute, along with corresponding recommendations for mitigation.

Table 11. Major sources of air pollution within the Messebo Cement Factory manufacturing process

Source Stage	**Primary Pollutants**	**Key Emission Activities**	**Recommendations**
Raw Material Handling	Particulate Matter (PM)	• Mining, drilling, blasting • Crushing and grinding • Transport and storage of raw materials • Homogenization and dosing	• Optimize water spraying systems • Enclose conveyors • Upgrade and maintain baghouse filters
Pyroprocessing (Kiln Stage)	CO_2, NO_x, SO_2	• Limestone calcination ($CaCO_3 \rightarrow CaO + CO_2$) • Fossil fuel combustion at >1400°C • Emissions from sulfur-bearing fuels and materials	• Improve combustion efficiency • Use alternative low-sulfur fuels • Adopt SCR or SNCR NO_x control technologies
Clinker Production & Cooling	Particulate Matter (PM), Trace CO & SO_2	• Material handling during clinker transfer • Dust from cooling fans and conveyors • Residual emissions during clinker formation	• Install enclosed transfer systems • Maintain cooling systems • Use efficient dust collection units
Bag Filter Operations	Particulate Matter (PM)	• Material handling, crushing, and packaging • Notable emission areas: raw mills, coal mills, and clinker units	• Expand filter coverage in packaging areas • Regularly maintain existing bag filters • Monitor filter performance for efficiency

Table 12 Dust control methods for each emission source activity at MCF

Emission sources	**Dust control method**
Limestone Unloading	No method
Limestone Crushing	No method
Limestone belt conveyor transfer point	Covered by an aluminum sheet
Limestone stacker/ reclaimer	No method
Coal Unloading	No method
Coal Crushing	Bag filter
Coal belt conveyor transfer point	Covered by an aluminum sheet and bag filters
Coal stacker/reclaimer	No method
Gypsum unloading operation	No method
Gypsum crusher	Bag filter
Gypsum belt conveyor transfer point	Covered by an aluminum sheet
Additive unloading	No control
Road dust	Paved road, clean, and wetting of unpaved roads
Coal Yard	No control
Clinker TP	Bag filter
Clinker Open Stockpiles	Cover Sheet
Silo Vents	Bag filter

Table 13 Activities with their bag filter

Activities with bag filters	**Number of activities**	**Total number of bag filters**
Crusher raw material	3	5
Transfer Points	4	2
Surge bin	1	2
Crusher Coal	1	1
Raw Mill	2	3
Coal Mill	2	6
Clinker	2	3
Cement Mill	5	7
Calciner	2	1
Packaging	8	4
Total		34

4.1.5. Analysis of Diseases trends at MCF

This section provides a detailed analysis of disease incidence and trends recorded at the MCF clinic between 2013 and 2017.

Respiratory Tract Infections (RTIs) : RTIs were the most prevalent condition at MCF, with annual cases ranging from 1,366 to 2,136. Percentages fluctuated between 17% and 22.4%, reflecting persistent exposure to airborne irritants such as dust, fine particulates, and chemical emissions. The peak in 2013 (22.4%) may reflect higher operational intensity or limited early mitigation, while subsequent reductions suggest slight improvements in workplace controls or reporting variations.

Dermatitis : Dermatitis was absent in 2013 but appeared in 2014 with 739 cases (9%) and remained steady through 2017 (732–795 cases, 8.6–10%). This emergence may indicate either increased skin sensitivity due to airborne chemical exposure or improvements in reporting practices. The persistent presence highlights the need for personal protective equipment (PPE) and hygiene interventions.

Ophthalmic Conditions: Eye-related cases were consistently reported, peaking at 978 cases (11.5%) in 2017. This trend suggests ocular irritation from dust, fumes, or poor ventilation, emphasizing the importance of eye protection and air quality management.

Intestinal Parasitosis (I/P) and Arthritis :I/P cases ranged from 804–956 annually (≈9–11%), while arthritis cases were generally lower, peaking at 702 (8%) in 2015. These conditions are less directly related to airborne exposure but indicate other occupational and health challenges, such as sanitation, nutrition, and ergonomic factors.

Genarlly, the dominance of RTIs, alongside emerging dermatitis and increasing ophthalmic conditions, strongly indicates that airborne exposure is a critical health risk at MCF. While partial improvements are evident, persistent exposure to dust, particulates, and chemical emissions continues to affect worker health. Non-airborne conditions highlight the importance of comprehensive occupational health measures, including both environmental control strategies and general health promotion interventions.

Table 14 Summary of Disease Cases and Corresponding Percentages Recorded at MCF

Year	Respiratory Tract Infection (RTI)Cases	RTI %	Intestinal Parasitosis (I/P) Cases	I/P %	Dermatitis Cases	Dermatitis %	Ophthalmic Conditions Cases	Ophthalmic %	Arthritis Cases	Arthritis %
2013	2136	22.4	943	10	NA	NA	847	9	NA	NA
2014	1366	17	804	10	739	9	795	10	NA	NA
2015	1742	18	956	11	795	10	771	12	702	8
2016	1749	20.9	894	10.6	778	9.3	768	9.2	604	7.2
2017	1630	19.1	809	9.5	732	8.6	978	11.5	NA	NA

4.2. Discussion

The findings of this study reveal that air pollution at Messebo Cement Factory PLC (MCF) presents both environmental and occupational health challenges. The analysis of air pollution control techniques and clinical health records collectively demonstrates that the current emission management strategies are inadequate to ensure regulatory compliance or safeguard worker health.

Emission Characteristics and Source Identification

The emission profile of MCF is consistent with global trends in cement manufacturing, where pyroprocessing and raw material handling remain the dominant sources of pollutants. Field measurements using the Yuante Gas Detector recorded high concentrations of CO_2, NO_x, SO_2, CO, and particulate matter (PM), particularly during rotary kiln operations. This aligns with the findings of Van Oss and Padovani (2002), who identified these production stages as the most emission-intensive. CO_2 emissions at MCF increased sharply from approximately 78,884 tonnes in 2000/01 to nearly 991,000 tonnes in 2015/16, tracking the expansion in clinker output and energy use. This trend supports the IPCC (2014) assertion that emission growth in the cement sector is directly linked to production intensity and fuel combustion.

The recorded PM concentrations at key points such as raw milling, pyroprocessing, and clinker storage reached up to 240 mg/Nm³, exceeding both Ethiopia's national limit of 150 mg/Nm³ and the WHO/IFC guideline of 50 mg/Nm³. Despite the installation of baghouse filters and fabric filters, these exceedances indicate gaps in system efficiency, maintenance, and operational control. The presence of visible dust accumulation in unenclosed or poorly ventilated sections further highlights fugitive emissions. Such findings confirm that, while the factory possesses modern emission-control technologies, performance is hindered by inadequate maintenance, weak enforcement, and insufficient environmental management practices.

Evaluation of Control Techniques and Institutional Performance

Although MCF employs standard emission control systems—such as bag filters and low-NO_x burners; their operational effectiveness appears limited. The study observed discrepancies between technological capability and actual performance**:** filters with rated efficiencies above 99% failed to maintain regulatory compliance. This suggests either poor system upkeep, improper sealing of ducts, or suboptimal process control. Similar observations have been reported in UNEP (2013) and Greer (2003), which emphasize that installation of advanced equipment alone does not guarantee pollution reduction without proper maintenance, training, and monitoring.

Survey data reinforced this conclusion, revealing that 65% of respondents frequently observed visible dust emissions, while 76% had never received environmental or safety training. Only 8% rated current mitigation measures as "very effective." These findings point to institutional weaknesses—notably limited environmental awareness, inadequate staff capacity, and insufficient regulatory follow-up. The reliance on high-sulfur coal as a primary fuel further exacerbates SO_2 emissions, reflecting missed opportunities for cleaner alternatives such as natural gas or biomass. Moreover, the absence of a continuous emissions monitoring system limits the factory's ability to track real-time performance and respond promptly to emission spikes.

Occupational Health Implications

The clinical data analysis provides strong evidence linking air quality deficiencies to occupational health outcomes. Respiratory Tract Infections (RTIs) consistently represented the most prevalent health condition among factory workers, peaking at 22.4% in 2013 and remaining above 17% throughout the study period (2013–2017). The emergence of dermatitis and the increasing incidence of ophthalmic conditions indicate chronic exposure to airborne particulates and chemical irritants. These patterns align with global occupational health literature, which identifies cement dust as a primary cause of respiratory irritation, mucosal inflammation, and dermal reactions in industrial environments.

The absence of dermatitis data in 2013 likely reflects underreporting or late recognition rather than an actual absence of cases. The upward trend in eye-related conditions suggests continuous exposure to fine particulates affecting mucosal membranes. Together, these health outcomes substantiate the environmental monitoring results, confirming that airborne exposure remains a critical risk at MCF. The parallel increase in emissions and disease prevalence underscores the interdependence between environmental control performance and worker health protection.

Integrated Interpretation and Implications

The combined environmental and health evidence demonstrates that MCF's air pollution management approach remains largely reactive rather than preventive. Although advanced pollution control technologies exist on-site, their effectiveness is compromised by operational inefficiencies, inadequate maintenance, and limited environmental governance. The findings emphasize that true emission reduction requires an integrated strategy combining engineering controls, institutional commitment, and occupational health management.

This study supports the view that sustainable emission control in the cement industry cannot rely solely on end-of-pipe technologies. Instead, it demands systemic interventions such as fuel substitution, process optimization, regular maintenance, continuous monitoring, and capacity building. Implementing structured training programs, enforcing PPE use, and institutionalizing health surveillance will significantly reduce exposure risks. Aligning MCF's practices with ISO 14001 and IFC/World Bank Environmental, Health, and Safety guidelines would enhance compliance and move the factory toward sustainable industrial performance.

Chapter 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study demonstrates that Messebo Cement Factory PLC (MCF), while vital to Ethiopia's industrial development, remains a significant contributor to air pollution and occupational health risks. The factory emits substantial levels of CO_2, NO_x, SO_2, CO, and particulate matter (PM), with pyroprocessing identified as the most emission-intensive stage due to limestone calcination and high-temperature combustion. Persistent fugitive dust from raw material handling and storage further exacerbates PM pollution, posing visible and measurable risks to workers and surrounding communities.

Three central challenges emerge from the findings. First, emission levels consistently exceed national and international standards, highlighting systemic regulatory non-compliance. Second, the partial deployment of pollution control technologies—such as baghouse filters and low-NO_x burners—is undermined by poor maintenance, inadequate monitoring, and limited staff training. Third, the rising CO_2 emissions, closely correlated with clinker output, underscore the climate burden of Ethiopia's fossil-fuel-intensive cement sector.

These environmental issues are compounded by occupational health concerns. Respiratory tract infections, dermatitis, and ophthalmic conditions are prevalent among factory workers, reflecting chronic exposure to airborne particulates and chemical irritants. The sustained prevalence of these conditions over multiple years underscores the urgent need for systemic interventions to protect worker health.

The combined evidence indicates that, while MCF has established a basic framework for pollution control, its effectiveness remains limited. Immediate corrective actions such as strengthening emission monitoring, improving dust management, and enhancing occupational health and safety programs are required. Concurrently, long-term structural reforms, including investments in cleaner technologies, alternative fuels, and staff capacity building, are essential to align MCF with sustainable industrial practices, safeguard worker well-being, and support Ethiopia's commitments to climate resilience and public health.

5.2. Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance environmental performance, reduce air pollutant emissions, and safeguard occupational health at Messebo Cement Factory PLC (MCF), while promoting sustainable operations and regulatory compliance:

- Upgrade of Air Pollution Control Systems : MCF should replace or retrofit existing baghouse filters with high-efficiency, self-cleaning fabric filters capable of capturing more than 99.99% of particulate matter (PM), particularly at critical emission points such as the kiln, mill, and cooler. These upgrades will reduce PM emissions, improve local air quality, and ensure compliance with national and international standards.

- Implementation of Continuous Emission and Health Monitoring Systems

  - Environmental Monitoring: Install Continuous Emission Monitoring Systems to track key pollutants (CO_2, NO_x, SO_2, PM) in real time, enabling process optimization, regulatory compliance, and timely corrective actions.
  - Occupational Health Monitoring: Establish scheduled respiratory, dermatological, and ophthalmic health screenings for all employees to detect early signs of exposure-related illnesses. Integration of air quality monitoring with real-time alerts will allow prompt intervention to protect worker health.

- Optimization of Kiln and Process Operations : introduce low-NO_x burner optimization, oxygen injection systems, and staged combustion techniques to minimize NO_x and CO emissions. The deployment of Advanced Process Control (APC) systems is recommended to stabilize critical operating parameters, reduce energy consumption, and further lower pollutant formation.

- Transition to Cleaner Energy and Alternative Materials : gradually replace high-sulfur coal with lower-emission fuels, such as biomass, natural gas, or waste-derived energy, to reduce gaseous emissions. Additionally, incorporating supplementary cementitious materials (e.g., calcined clay, slag, or fly ash) can lower the clinker-to-cement ratio and decrease CO_2 emissions from clinker production.

- Control of Fugitive Dust Emissions : all material transfer points should be enclosed, with dust suppression systems (e.g., water misting or foaming agents) installed in high-risk areas. Regular maintenance and sealing of conveyor belts, silos, and crushers are essential to minimize fugitive PM emissions.

- Institutional Strengthening and Capacity Building : establish a dedicated Environmental and Occupational Health Compliance Unit to oversee monitoring, reporting, and implementation of mitigation measures. Conduct regular environmental and safety training programs for employees, covering emission control, waste management, and occupational health practices.

- Stakeholder Engagement and Regulatory Collaboration :engage periodically with local communities through consultations and environmental impact assessments to address public concerns. Strengthen collaboration with regulatory bodies, such as the FDRE Environmental Protection Authority (EPA), to ensure compliance with evolving standards and to leverage technical support for innovative pollution control technologies.

Overall, the integrated implementation of these recommendations is both technically and economically feasible. They align with national environmental objectives and international best practices, while simultaneously improving worker health, reducing environmental impacts, and advancing MCF toward sustainable and responsible cement production operations.

References

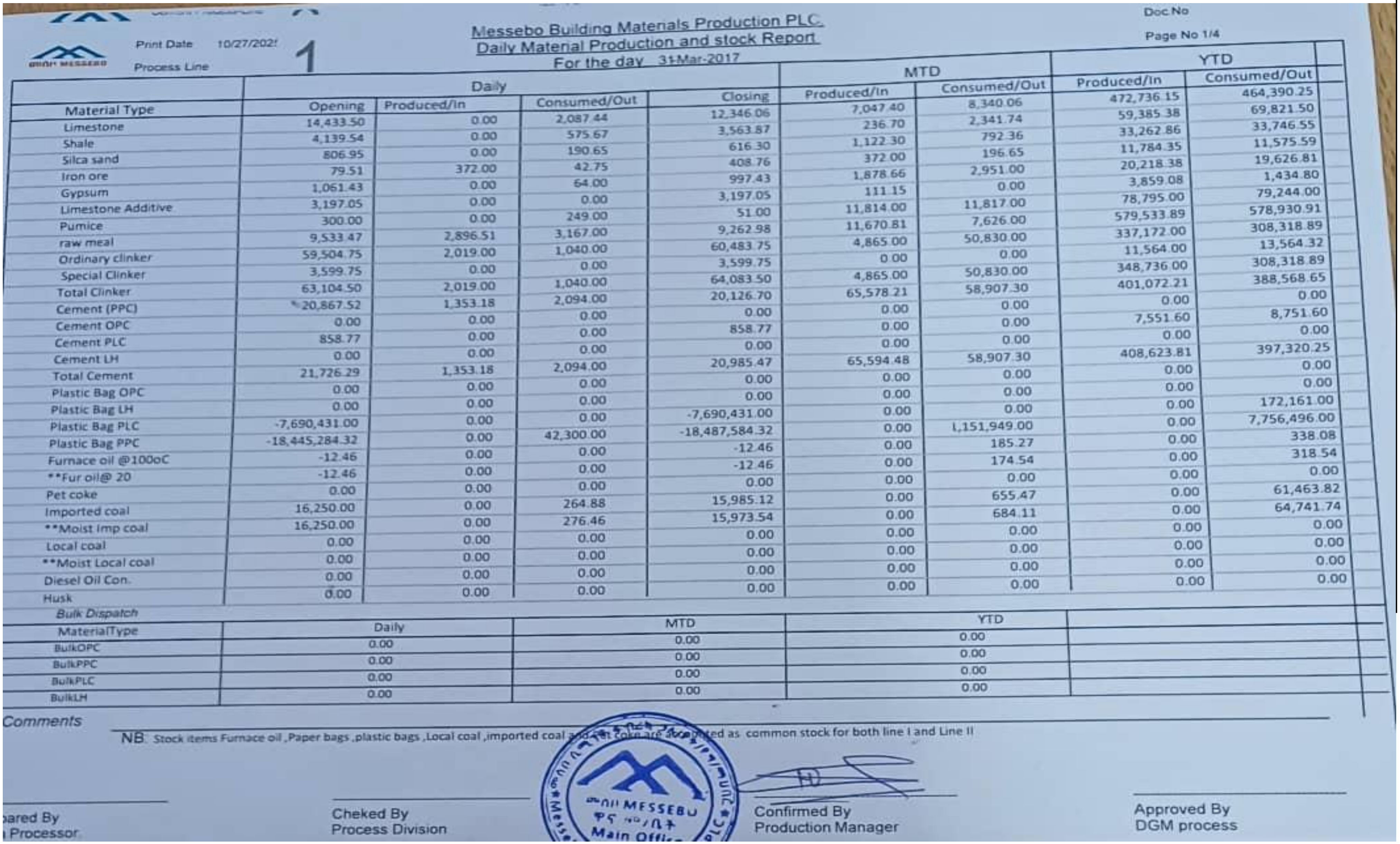
- Abu-Allaban, M., & Abu-Qudais, H. (2011). Impact assessment of ambient air quality by cement industry: A case study in Jordan. *Aerosol and Air Quality Research, 11(7), 802–810.
- Ali, N., Jaffar, A., Anwer, M., Khan, S., Anjum, M., Hussain, A., ... & Ming, X. (2015). The greenhouse gas emissions produced by cement production and its impact on environment: A review of global cement processing. *International Journal of Research (IJR), 2*(2).
- Andrew, R. M. (2018). Global CO_2 emissions from cement production, 1928–2017. *Earth System Science Data, 10*(4), 2213–2239.
- Ashley, M., & Price, L. (2008, June). Use of alternative fuels in cement manufacture: Analysis of fuel characteristics and feasibility for use in the Chinese cement sector.
- Belete, F., Mekonnen, M., & Alemu, G. (2020). Inorganic fertilizers and their impact on soil fertility. *Ethiopian Journal of Agricultural Sciences, 30*(3), 67–78.
- Benjamin, J. (2005). Wind data evaluation after 6 months. *Wind Energy Programme, TERNA-GTZ GmbH*.
- Berhe, A., Alemayehu, T., & Fortuin, K. J. P. (2014). Environmental impact study of cement factory using a multi-criteria analysis: Evidence from Messebo Cement Factory, Ethiopia. *Developing Country Studies, 4*(24), 151–161.
- Bye, G. C. (2011). *Portland Cement* (3rd ed.). London: Thomas Telford Limited.
- Cicek, A., & Koparala, I. (2004). Accumulation of sulphur and heavy metals in soil and tree leaves sampled from the surroundings of Tunçbilek Thermal Power Plant. *Chemosphere, 57*, 1031–1036.
- Federal Democratic Republic of Ethiopia (FDRE). (2011). *Climate Resilient Green Economy (CRGE) Strategy*. Addis Ababa.
- Fitsum Consultancy Services. (2008). *Environmental Impact Assessment Report: Case of National Cement Share Company*.
- F.L. Smidth & Co. AS. (n.d.). *Packing Plant Maintenance, Trainers Manual*.
- Fujii, H., Managi, S., & Kaneko, S. (2013). Decomposition analysis of air pollution abatement in China: Empirical study for ten industrial sectors from 1998 to 2009. *Journal of Cleaner Production, 59*, 22–31.

- Gebreslassie, M. G., Bahta, S. T., & Mihrete, A. S. (2023). Development of alternative fuel for cement industries: The case of Messebo cement factory in Ethiopia. *Waste Management Bulletin, 1*(3), 58–70.
- Gleb, G. M. (2007). Improved cement quality and grinding efficiency by means of closed mill circuit modeling [Master's thesis, Texas University].
- IEA. (2018). *Technology Roadmap Low-Carbon Transition in the Cement Industry*. Paris: International Energy Agency.
- IPCC. (2005). *Carbon dioxide capture and storage*. Cambridge University Press.
- Jeroen, K. (2009). Cement production: *EMEP/EEA emission inventory guidebook*.
- Jones, R. (1993). Locating and estimating air emissions from sources of cadmium and cadmium compounds. *U.S. Environmental Protection Agency*.
- Karbassi, A. R., Jafari, H. R., Yavari, A. R., Hoveidi, H., & Kalal, H. S. (2010). Reduction of environmental pollution through optimization of energy use in cement industries. *International Journal of Environmental Science & Technology, 7*, 127–134.
- Kumar, S., & Katoria, D. (2013). Air pollution and its control measures. *International Journal of Environmental Engineering and Management, 4*(5), 445–450.
- Liang, J., Chen, C., Song, X., Han, Y., & Liand, Z. (2011). Assessment of heavy metal pollution in soil and plant from Dunhua sewage irrigation area. *International Journal of Electrochemical Science, 6*, 5314–5325.
- Liu, X., Yang, L., Du, J., Zhang, H., Hu, J., Chen, A., & Lv, W. (2024). Carbon and air pollutant emissions forecast of China's cement industry from 2021 to 2035. *Resources, Conservation and Recycling, 204*, 107498.
- Messebo Expansion Project. (n.d.). *Process Training Manual*.
- Mishra, U. C., Sarsaiya, S., & Gupta, A. (2022). A systematic review on the impact of cement industries on the natural environment. *Environmental Science and Pollution Research, 29*(13), 18440–18451.
- Murray, A., & Price, L. (2008). Use of alternative fuels in cement manufacture: Analysis of fuel characteristics and feasibility for use in the Chinese cement sector.
- Nor Sharliza, M. S., Zainura, Z. N., Haslenda, H., Zaini, U., & Juhaizah, T. (2010). Emission control systems in chemical engineering applications. *Universiti Teknologi Malaysia*.
- Philip, A. (2001). *The Cement Plant Operations Handbook* (3rd ed.). Cement Review.

- Reitemeyer, I. (2005). New high efficiency dust collectors at the Holcim-owned Dudfield. *Cement Work ZKG, 8, 1–6.
- Samuel, E., & Aynalem, D. (2012). Assessing the effect of cement dust emission on the physicochemical nature of soil around Messebo area, Tigray, Ethiopia. *International Journal of Economic and Environmental Geology, 3*(2), 12–20.
- Siegbert, S. (2012). Cement. In *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH.
- Themelis, N. J. (2013). Energy, environmental and greenhouse gas effects of using alternative fuels in cement production. *Columbia University*.
- Van Oss, H. G., & Padovani, A. C. (2002). Cement manufacture and the environment, Part I: Chemistry and technology. *Journal of Industrial Ecology, 6*(1), 89–105.
- World Health Organization. (2006). *Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. World Health Organization.
- Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment, 26*(1), 303–329.
- Zimwara, D., Mugwagwa, L., & Chikowore, T. R. (2012). Air pollution control techniques for the cement manufacturing industry: A case study for Zimbabwe. *Department of Industrial and Manufacturing Engineering, National University of Science and Technology, Zimbabwe*.

Appendix

Appendix 1: Daily Production and Material Stock Report of Line 1



Messebo Building Materials Production PLC.
Daily Material Production and stock Report
For the day 31-Mar-2017

Print Date 10/27/202!

Process Line 1

Doc No

Page No 1/4

	Daily				MTD		YTD	
Material Type	Opening	Produced/In	Consumed/Out	Closing	Produced/In	Consumed/Out	Produced/In	Consumed/Out
Limestone	14,433.50	0.00	2,087.44	12,346.06	7,047.40	8,340.06	472,736.15	464,390.25
Shale	4,139.54	0.00	575.67	3,563.87	236.70	2,341.74	59,385.38	69,821.50
Silca sand	806.95	0.00	190.65	616.30	1,122.30	792.36	33,262.86	33,746.55
Iron ore	79.51	372.00	42.75	408.76	372.00	196.65	11,784.35	11,575.59
Gypsum	1,061.43	0.00	64.00	997.43	1,878.66	2,951.00	20,218.38	19,626.81
Limestone Additive	3,197.05	0.00	0.00	3,197.05	111.15	0.00	3,859.08	1,434.80
Pumice	300.00	0.00	249.00	51.00	11,814.00	11,817.00	78,795.00	79,244.00
raw meal	9,533.47	2,896.51	3,167.00	9,262.98	11,670.81	7,626.00	579,533.89	578,930.91
Ordinary clinker	59,504.75	2,019.00	1,040.00	60,483.75	4,865.00	50,830.00	337,172.00	308,318.89
Special Clinker	3,599.75	0.00	0.00	3,599.75	0.00	0.00	11,564.00	13,564.32
Total Clinker	63,104.50	2,019.00	1,040.00	64,083.50	4,865.00	50,830.00	348,736.00	308,318.89
Cement (PPC)	20,867.52	1,353.18	2,094.00	20,126.70	65,578.21	58,907.30	401,072.21	388,568.65
Cement OPC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cement PLC	858.77	0.00	0.00	858.77	0.00	0.00	7,551.60	8,751.60
Cement LH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Cement	21,726.29	1,353.18	2,094.00	20,985.47	65,594.48	58,907.30	408,623.81	397,320.25
Plastic Bag OPC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plastic Bag LH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plastic Bag PLC	-7,690,431.00	0.00	0.00	-7,690,431.00	0.00	0.00	0.00	172,161.00
Plastic Bag PPC	-18,445,284.32	0.00	42,300.00	-18,487,584.32	0.00	1,151,949.00	0.00	7,756,496.00
Furnace oil @100oC	-12.46	0.00	0.00	-12.46	0.00	185.27	0.00	338.08
**Fur oil@ 20	-12.46	0.00	0.00	-12.46	0.00	174.54	0.00	318.54
Pet coke	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Imported coal	16,250.00	0.00	264.88	15,985.12	0.00	655.47	0.00	61,463.82
**Moist imp coal	16,250.00	0.00	276.46	15,973.54	0.00	684.11	0.00	64,741.74
Local coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
**Moist Local coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel Oil Con.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Husk	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Bulk Dispatch

MaterialType	Daily	MTD	YTD
BulkOPC	0.00	0.00	0.00
BulkPPC	0.00	0.00	0.00
BulkPLC	0.00	0.00	0.00
BulkLH	0.00	0.00	0.00

Comments

NB: Stock items Furnace oil ,Paper bags ,plastic bags ,Local coal ,imported coal and Pet coke are accounted as common stock for both line I and Line II

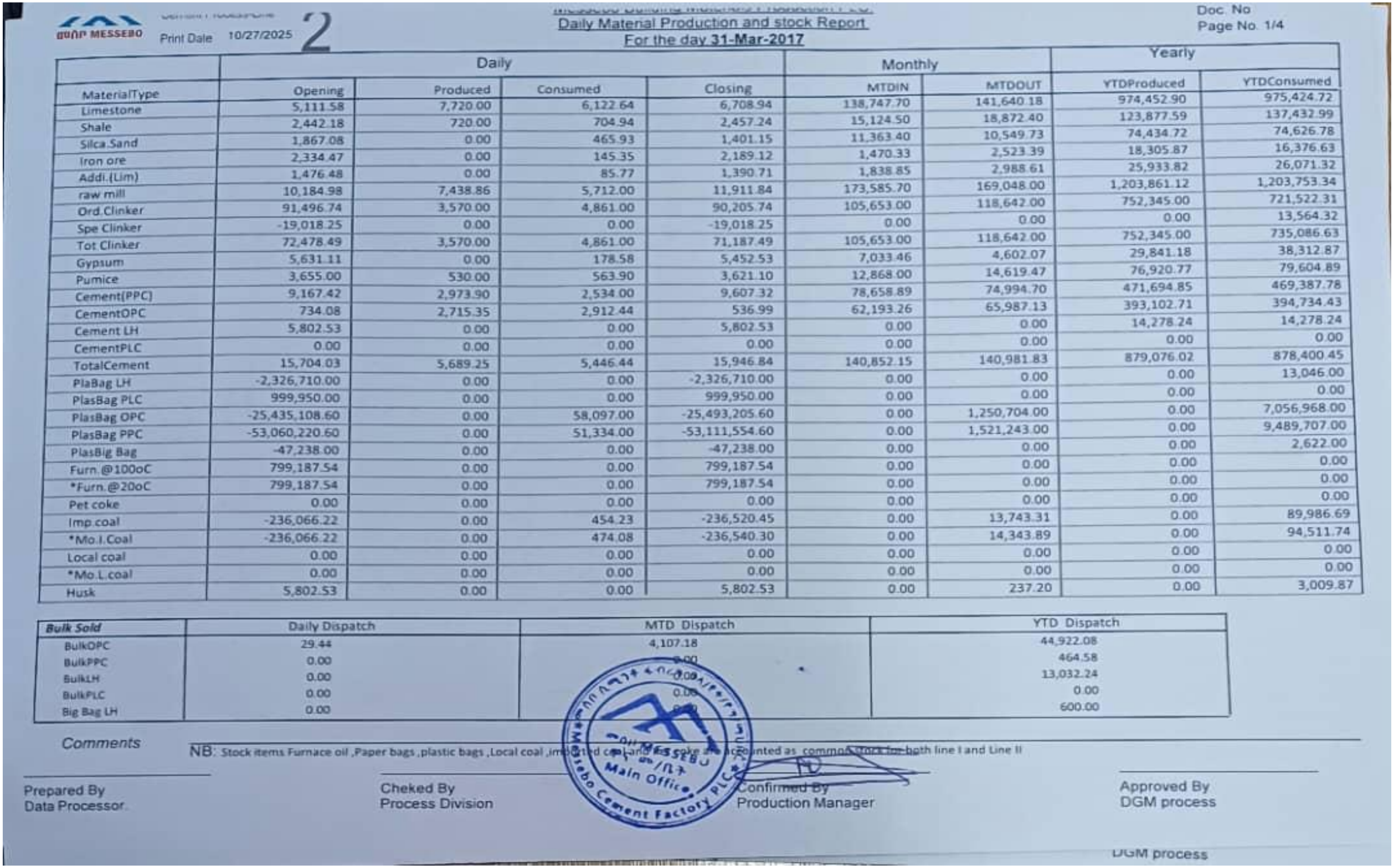
ared By
Processor

Cheked By
Process Division

Confirmed By
Production Manager

Approved By
DGM process

Appendix 2: Daily Production and Material Stock Report of Line 2



MESSEBO

Print Dale 10/27/2025 2

Daily Material Production and stock Report
For the day **31-Mar-2017**

Doc. No
Page No. 1/4

	Daily				Monthly		Yearly	
MaterialType	Opening	Produced	Consumed	Closing	MTDIN	MTDOUT	YTDProduced	YTDConsumed
Limestone	5,111.58	7,720.00	6,122.64	6,708.94	138,747.70	141,640.18	974,452.90	975,424.72
Shale	2,442.18	720.00	704.94	2,457.24	15,124.50	18,872.40	123,877.59	137,432.99
Silca.Sand	1,867.08	0.00	465.93	1,401.15	11,363.40	10,549.73	74,434.72	74,626.78
Iron ore	2,334.47	0.00	145.35	2,189.12	1,470.33	2,523.39	18,305.87	16,376.63
Addi.(Lim)	1,476.48	0.00	85.77	1,390.71	1,838.85	2,988.61	25,933.82	26,071.32
raw mill	10,184.98	7,438.86	5,712.00	11,911.84	173,585.70	169,048.00	1,203,861.12	1,203,753.34
Ord.Clinker	91,496.74	3,570.00	4,861.00	90,205.74	105,653.00	118,642.00	752,345.00	721,522.31
Spe Clinker	-19,018.25	0.00	0.00	-19,018.25	0.00	0.00	0.00	13,564.32
Tot Clinker	72,478.49	3,570.00	4,861.00	71,187.49	105,653.00	118,642.00	752,345.00	735,086.63
Gypsum	5,631.11	0.00	178.58	5,452.53	7,033.46	4,602.07	29,841.18	38,312.87
Pumice	3,655.00	530.00	563.90	3,621.10	12,868.00	14,619.47	76,920.77	79,604.89
Cement(PPC)	9,167.42	2,973.90	2,534.00	9,607.32	78,658.89	74,994.70	471,694.85	469,387.78
CementOPC	734.08	2,715.35	2,912.44	536.99	62,193.26	65,987.13	393,102.71	394,734.43
Cement LH	5,802.53	0.00	0.00	5,802.53	0.00	0.00	14,278.24	14,278.24
CementPLC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TotalCement	15,704.03	5,689.25	5,446.44	15,946.84	140,852.15	140,981.83	879,076.02	878,400.45
PlaBag LH	-2,326,710.00	0.00	0.00	-2,326,710.00	0.00	0.00	0.00	13,046.00
PlasBag PLC	999,950.00	0.00	0.00	999,950.00	0.00	0.00	0.00	0.00
PlasBag OPC	-25,435,108.60	0.00	58,097.00	-25,493,205.60	0.00	1,250,704.00	0.00	7,056,968.00
PlasBag PPC	-53,060,220.60	0.00	51,334.00	-53,111,554.60	0.00	1,521,243.00	0.00	9,489,707.00
PlasBig Bag	-47,238.00	0.00	0.00	-47,238.00	0.00	0.00	0.00	2,622.00
Furn.@100oC	799,187.54	0.00	0.00	799,187.54	0.00	0.00	0.00	0.00
*Furn.@20oC	799,187.54	0.00	0.00	799,187.54	0.00	0.00	0.00	0.00
Pet coke	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Imp.coal	-236,066.22	0.00	454.23	-236,520.45	0.00	13,743.31	0.00	89,986.69
*Mo.I.Coal	-236,066.22	0.00	474.08	-236,540.30	0.00	14,343.89	0.00	94,511.74
Local coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
*Mo.L.coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Husk	5,802.53	0.00	0.00	5,802.53	0.00	237.20	0.00	3,009.87

Bulk Sold	Daily Dispatch	MTD Dispatch	YTD Dispatch
BulkOPC	29.44	4,107.18	44,922.08
BulkPPC	0.00	0.00	464.58
BulkLH	0.00	0.00	13,032.24
BulkPLC	0.00	0.00	0.00
Big Bag LH	0.00	[illegible]	600.00

Comments

NB: Stock items Furnace oil ,Paper bags ,plastic bags ,Local coal ,imported coal and Pet coke are accounted as common stock for both line I and Line II

Prepared By
Data Processor

Cheked By
Process Division

Confirmed By
Production Manager

Approved By
DGM process

DGM process

Appendix 3: Airborne Dust Levels Across Cement Production Stages at Messebo Cement Factory, Tigray

Introduction

The objective of this section is to integrate observational data with corresponding survey findings to provide a comprehensive assessment of workplace environmental quality. Specifically, it aims to define the total population and sample size utilized in the study, thereby ensuring the methodological rigor, reliability, and validity of the data analysis. This approach supports evidence-based evaluation and strengthens the credibility of the overall research outcomes.

1. Position: ______________________ Sex: _____________ Age: _________
2. Work Experience: ______________________
3. **Which area of the factory do you work in or are familiar with?**

   ☐ Raw material acquisition ☐ Production line

   ☐ Clinker production and cooling ☐ Waste management and disposal

   ☐ General management/Other ☐ Not applicable
4. **Have you noticed visible dust or emissions from the factory as staff member?**

   ☐ Yes ☐ No ☐ Not Sure
5. **In your opinion, how effective are the current dust and emission control measures at MCF?**

   ☐ Very effective ☐ Moderately effective

   ☐ Slightly effective ☐ Not effective

   ☐ Not Sure
6. **How frequently do you observe dust emissions similar to those shown in Figure 9 during your daily operations?**

   ☐ Very frequently ☐ Frequently ☐ Occasionally ☐ Rarely

   ☐ Never

7. **Have there been any improvements in air pollution control at MCF over the past year?**

☐ Significant improvements ☐ Moderate improvements

☐ Minor improvements ☐ No improvements ☐ Not Sure

8. **Which of the following measures do you believe would most effectively reduce emissions and dust at MCF?** (You may select more than one.)

☐ Improved filtration systems ☐ Regular maintenance of equipment

☐ Training for employees on environmental best practices

☐ Better raw material handling procedures

☐ Enhanced monitoring and enforcement of environmental standards

☐ Investment in new technology

9. **Have you received training on environmental management and pollution control?**

☐ Yes ☐ No ☐ Not Sure

10. **Would you say that the surrounding community is aware of the air pollution issues at MCF?**

☐ Very aware ☐ Somewhat aware ☐ Barely aware ☐ Not aware

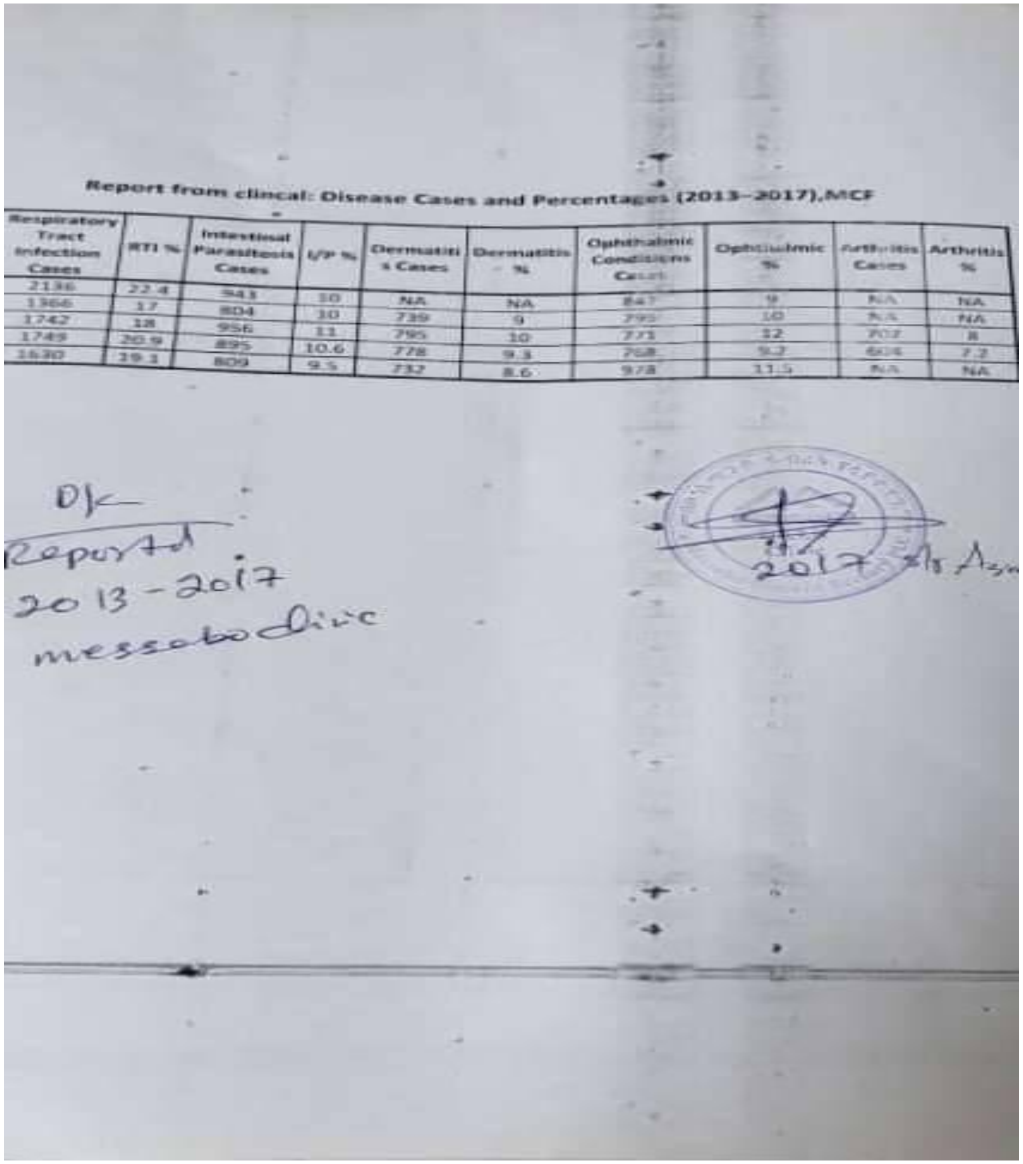
☐ Not Sure

11. **How supportive do you think management is regarding initiatives to improve air quality at the factory?**

☐ Very supportive ☐ Somewhat supportive

☐ Neutral ☐ Not supportive ☐ Not Sure

Appendix 4: Report from clincal: Disease Cases and Percentages (2013–2017),MCF



Report from clincal: Disease Cases and Percentages (2013–2017),MCF

Respiratory Tract Infection Cases	RTI %	Intestinal Parasitosis Cases	I/P %	Dermatitis Cases	Dermatitis %	Ophthalmic Conditions Cases	Ophthalmic %	Arthritis Cases	Arthritis %
2136	22.4	943	10	NA	NA	847	9	NA	NA
1366	17	804	10	739	9	795	10	NA	NA
1742	18	956	11	795	10	771	12	702	8
1749	20.9	895	10.6	778	9.3	768	9.2	604	7.2
1630	19.1	809	9.5	732	8.6	978	11.5	NA	NA

Ok
Reported
2013 - 2017
messobo clinic

2017

Appendix 5: Enviromental Policy

መሰቦ MESSEBO

ENVIRONMENTAL POLICY

Messebo Cement Factory PLC (MCF) is one of the leading cement factory, producing quality cement (ESEN 197-1-2013 standard) to immortal the country's grand projects and other construction industry at large by realizing a theme, quality in action. MCF plays a role on generating qualified industrial manpower for the country's industry development as well.

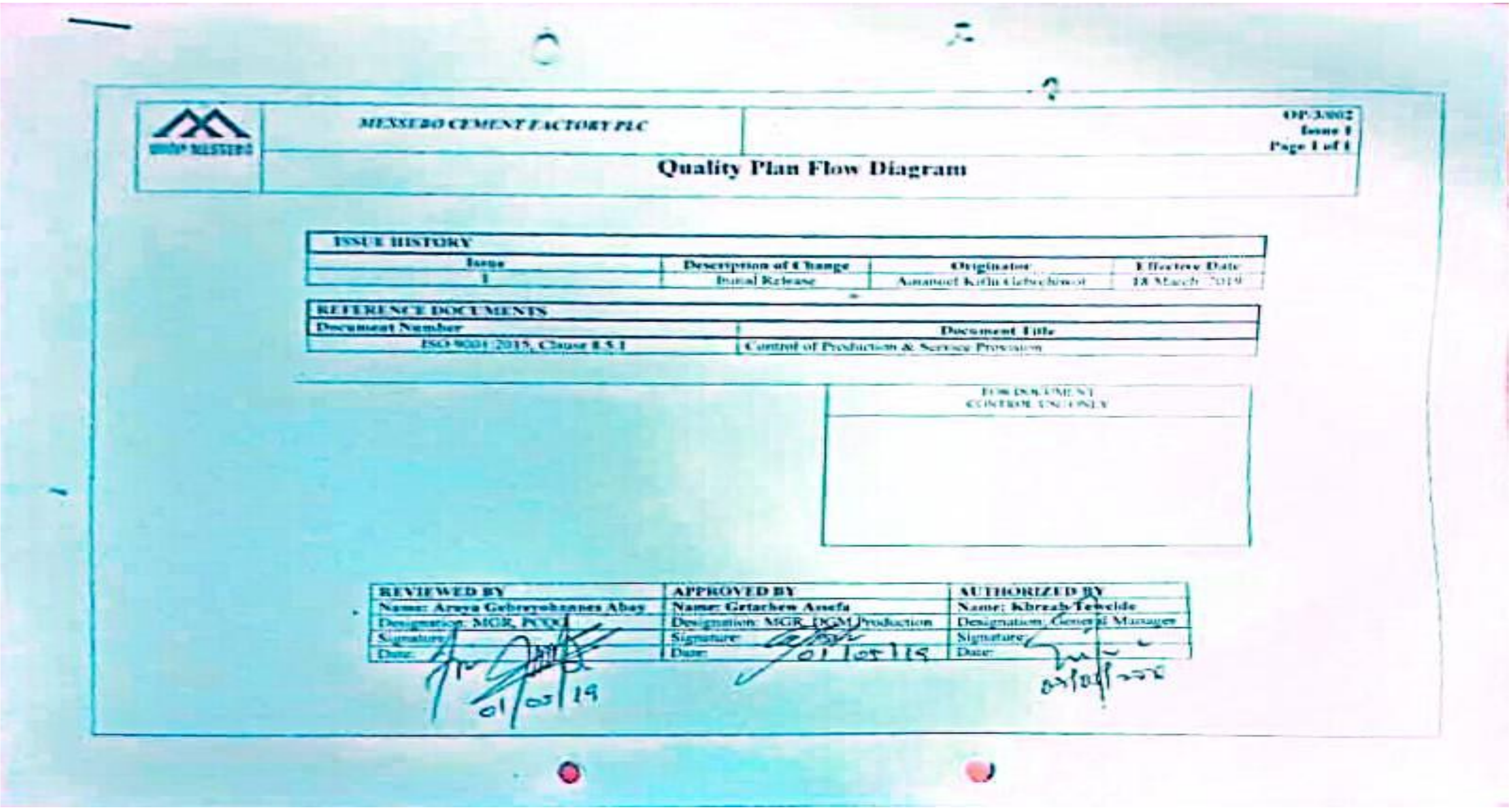
MCF is committed to produce cement economically in an eco-friendly. It is committed to sustainable cement production and minimizes any adverse impact on the environment resulting from our production activities. To minimize environmental impacts concerning our activities, products and services, the company shall:-

- Comply with applicable environmental legal obligations and other requirements to which the company subscribes which relate to its environmental aspects.
- Protect the environment by adhering to the practices of pollution prevention and reduction, waste management and resource consumption minimization and optimization.
- Educate, train, participate and motivate employees to carry out tasks in an environmentally responsible manner.

The Company is committed to continual improvement of its environmental performance through periodic reviewing. This Policy will be communicated to all interested parties and be available for the public.

KibreabTewelede
General Manager
Date: 20|03|17

Appendix 6: Quality Plan Flow Diagram



MESSEBO	*MESSEBO CEMENT FACTORY PLC*	OP-3/002 Issue 1 Page 1 of 1
	Quality Plan Flow Diagram	

ISSUE HISTORY			
Issue	**Description of Change**	**Originator**	**Effective Date**
1	Initial Release	Amanuel Kiflu Gebrehiwot	18 March 2019

REFERENCE DOCUMENTS	
Document Number	**Document Title**
ISO 9001:2015, Clause 8.5.1	Control of Production & Service Provision

FOR DOCUMENT CONTROL USE ONLY

REVIEWED BY	**APPROVED BY**	**AUTHORIZED BY**
Name: Araya Gebreyohannes Abay	**Name: Getachew Assefa**	**Name: Kibreab Tewelde**
Designation: MGR, PCQC	Designation: MGR, DGM Production	Designation: General Manager
Signature:	Signature:	Signature:
Date: 01/05/19	Date: 01/05/19	Date: [illegible]

MESSEBO CEMENT FACTORY PLC

OP/3/002
Issue 1
Page 2 of 1

Quality Plan Flow Diagram