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**COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY
SCHOOL OF BUILT ENVIRONMENT
DEPARTMENT OF CONSTRUCTION ECONOMICS AND
MANAGEMENT**

***ASSESSING THE IMPACT OF BIOMASS ON GASEOUS EMISSIONS
FROM TRADITIONAL BRICK KILNS***

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Fulfilment for The Award of a Degree of Master of Science in Construction Management of
Makerere University.***

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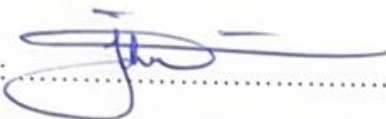
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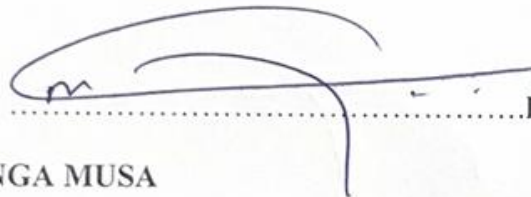
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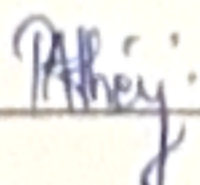
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DEDICATION

I would like to dedicate this research report to my late father Jackson Twinomujuni. May you live on through my success. Furthermore, I dedicate it to my mom and siblings for their financial support, prayers and love in my academic journey and my friends for their inspiration.

May the Almighty God bless them.

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LIST OF ACRONYMS

ASTM – Standard Test Methods for Analysis of Wood Fuels

BC – Black Carbon

CEDAT – College of Engineering, Design, Art and Technology

CH₄ – Methane

CO – Carbon monoxide

CO₂ – Carbon dioxide

GHG – Green House Gases

GKMA – Greater Kampala Metropolitan Area

GoU – Government of Uganda

HHV – Higher Heating Value

MLR – Multiple Linear Regression

NDC – Nationally Determined Contributions

NO – Nitric Oxide

NO_x – Nitrogen oxides

PM – Particulate Matter

SDGs – Sustainable Development Goals

SO_x – Sulfur oxides

ABSTRACT

The traditional brick making process remains essential to Uganda's construction sector and primarily depends on the burning of biomass fuels, such as hardwood in clamp kilns, which are temporary and unregulated. However, the environmental implications of this process, particularly pollutant emissions during firing, remain underexplored. This study, therefore, addresses this gap by assessing the impact of biomass on gaseous emissions from traditional brick kilns in the Ugandan construction sector. The study employed a cross-sectional design that involved field-based emission measurement to obtain CO₂, CO, NO and NO_x; and laboratory tests to obtain the calorific value and moisture content of hardwood samples. Emissions were measured for approximately 2 hours per kiln using a flue gas analyzer across 63 traditional kilns in the Greater Kampala Metropolitan Area (GKMA).

The results demonstrate that hardwood biomass, mainly species like eucalyptus and mugavu, is dominating owing to its availability and energy content. Nonetheless, poor combustion technology, together with the increasing moisture content of certain biomass varieties, result in increased emissions. Fuel moisture content varied from 11-18%, with calorific values ranging from 11-27 MJ/Kg. Fuel quantities used were between 2.3 to 12.65 tonnes. Higher moisture content was negatively associated with calorific value and fuel quantity used, suggesting potential pre-combustion preparation issues impacting kiln efficiency and emissions. Emissions analysis revealed significant CO (273-3,899 ppm) and CO₂ (4,716-91,786 ppm) concentrations, indicative of inefficient combustion. NO_x was negligible due to low nitrogen in the fuel. Fuel-based emission factors were 18.81 ± 9.84 g/kg for CO and 500.82 ± 313.85 g/kg for CO₂. Moisture content and calorific value significantly influenced CO emissions, while only calorific value impacted CO₂. This research addresses a critical knowledge deficiency in Uganda's emissions inventory and advocates for the advancement of cleaner biomass alternatives and enhanced kiln designs. The findings serve as a significant reference for environmental regulators, architects, and quantity surveyors aiming to integrate sustainability indicators into building procurement and materials planning.

CHAPTER ONE: INTRODUCTION

1.1 Background

Brick production is an integral part in construction worldwide due to its extensive utilization as a source of durable and economical and locally sourced building materials. The manufacture of bricks, especially through traditional techniques, has increasingly raised concerns over its sustainability impacts (Bhat et al., 2014; International Finance Corporation, 2023). The construction sector worldwide is also a significant consumer of energy and natural resources, responsible for roughly 40% of global energy-related carbon dioxide (CO₂) emissions and nearly 36% of total energy consumption (IEA and UNEP, 2018). This further establishes the necessity for more sustainable construction approaches that guarantee cheap housing while minimizing environmental destruction.

Global initiatives like the United Nations Sustainable Development Goals (SDGs) underscore the necessity of reconciling development with environmental sustainability. SDG 7 argues for cheap and clean energy, SDG 11 emphasizes sustainable cities and communities, SDG 12 encourages responsible consumption and production, and SDG 13 underscores the necessity for urgent action on climate change (United Nations, 2015). The production of bricks is closely aligned with these objectives because to its significant reliance on natural resources, contribution to greenhouse gas emissions, and effects on ecosystems (Bond et al., 2013; Zavala et al., 2018). Consequently, enhancing methods in brick production is also integral to the wider global initiative for sustainable construction (Weyant et al., 2016).

In several low and middle income nations, traditional brick making persists owing to its affordability and accessibility. However, dependence on inefficient kilns, such as clamp kilns, results in significant emissions which negatively impact the environment and public health (Ventura et al., 2022). Research in South Asia has demonstrated that brick kilns represent significant stationary sources of black carbon emissions, impacting both climate and health (World Bank, 2011). The difficulty of mitigating emissions from brick kilns is not confined to one nation but is a broader worldwide issue associated with excessive energy consumption, climate change, and environmental degradation.

Uganda's burnt clay brick industry has flourished due in great part to the country's abundant clay resources, favorable climatic and environmental conditions, and workforce availability (Africa

Development Associates, 2017). However, traditional burnt brick production, which is prevalent in the country, is associated with processes which have raised environmental concerns due to their contribution to air pollution (UNEP, 2016). These processes lead to the release of greenhouse gases (GHGs), such as methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O). One of the processes associated with traditional burnt brick production is the use of biomass as a fuel type. Biomass-based energy sources dominate the nation's energy supply, accounting for about 95% of the primary energy used while petroleum products make up 1% and electricity 4%, respectively with the vast majority of Ugandans lacking access to modern energy sources and because of this, Uganda, like most other sub-Saharan African countries, largely utilizes biomass as a fuel source (Adeyemi & Asere, 2014).

Traditional brick-making in Uganda, particularly in rural areas, heavily relies on biomass as the primary fuel source in clamp kilns (Nekesa, 2018). The biomass, especially wood fuel, used in these kilns is often sourced from unsustainable practices such as deforestation and therefore exacerbates the environmental impact and contributes significantly to GHG emissions and environmental degradation. According to Bamwesigye et al. (2020), the major cause of deforestation in Uganda is for charcoal and firewood fuel biomass utilization. The above occurrences have therefore contributed to the decline of the forest cover in Uganda from 5 million hectares to 3.6 million hectares between 1990 and 2010 (Magala, 2014). The use of biomass in kilns raises critical concerns about sustainability, particularly in meeting Uganda's development goals without exacerbating environmental issues.

This research, therefore, aimed to understand the biomass utilization, explore the relationship between this biomass utilization and emissions in the Ugandan burnt brick production sector while further developing a predictive model for emissions from the findings. The study sought to assess the different characterizations of biomass and how they contribute to emissions in brick kilns and to identify ways in which the construction industry can minimize the negative impacts while enhancing sustainability.

1.2 Research Problem Statement

Continuous growth of Uganda's population has led to the significant development of the building sector, which has further raised demand for locally made bricks. Approximately 69% of households in Uganda are characterized by dwellings that have brick walls. The building sector in Uganda continues to rely significantly on traditional brick-making techniques to obtain these bricks which has further resulted in the demand for biomass as fuel. While these practices sustain local economies and address increasing construction demands, they are associated with gaseous emissions, majority of which are attributed to the combustion of fuel used and kiln designs.

Uganda is estimated to be using about 6 million tonnes of wood in the brick production industry annually. Roughly 79% of the biomass energy utilized globally comes from wood and other agricultural biomass. This has therefore contributed to environmental degradation through increased deforestation and carbon dioxide emissions, exacerbating the environmental challenges, including air pollution and climate change. It also poses health risks to the neighboring populations where communities next to brick kiln operations reportedly see declining air quality, associated with respiratory ailments, cardiovascular problems, and other health consequences.

However, despite its widespread use, there is limited understanding on the impact of the biomass characteristics on these emissions from traditional brick kilns, leaving gaps in understanding the carbon footprint of this vital sector in Uganda. Majority of the research on emissions has been focused on kiln design and fuels, mainly coal, in other regions such as South Asia and South America. To date, no study has been carried out to provide data on the levels of emissions from traditional kilns in Uganda, where biomass is the predominant fuel and how they differ due to the locally available biomass types and their properties. Therefore, there is a need to assess the emissions generated from biomass fueled kilns, as the demand for bricks keeps increasing, otherwise the air pollution will keep going unchecked which is detrimental. The findings can guide on the potential improvements in kiln operations through fuel efficiency to reduce environmental impacts.

1.3 General Objective

The primary objective of this research was to assess the impact of biomass on gaseous emissions from traditional brick kilns in the Ugandan construction sector.

1.4 Specific Objectives

- i. To characterize the biomass used in traditional brick kilns.
- ii. To determine the emissions from biomass-fueled traditional brick kilns.
- iii. To determine the influence of biomass characteristics on emissions from traditional brick kilns.

1.5 Research questions

The study sought to address the following research questions:

- i. What are the key characteristics (e.g., moisture content, calorific value) of biomass fuel used in burnt brick production?
- ii. What are the emission levels associated with the biomass used in brick kilns?
- iii. How do the characteristics of biomass influence the emissions during the brick production process?

1.6 Conceptual Framework

By outlining the connections between the variables being studied, a conceptual framework gives a study its theoretical and analytical foundation (Adom et al., 2018). It emphasizes the function of mediating or moderating elements and explains how independent variables are anticipated to affect dependent outcomes (Miles et al., 2014). This section illustrates the relationship between the characteristics of biomass fuels utilized in traditional brick kilns and the resultant emissions. The biomass characteristics, mainly the type of biomass (e.g. hardwood, softwood) and physical characteristics are crucial in influencing combustion behavior and, therefore, the volume of emissions generated during brick firing.

The impact of biomass on emissions is interconnected. A set of external operational parameters, including as kiln design, operational practices, and surrounding environmental conditions are moderating variables. The design of the kiln is crucial in influencing combustion efficiency. Traditional kilns, including clamp kilns, frequently lack insulation and air regulation systems, leading to elevated pollution emissions. Enhanced kiln technologies, conversely, can optimize combustion efficiency and diminish pollutant emissions, even while utilizing the same biomass type. Operational techniques, including brick stacking and airflow regulation, affect the thoroughness of combustion and emission characteristics. Furthermore, ambient conditions including temperature, relative humidity, wind speed and direction are treated as moderating

variables in this study, given their role in shaping combustion efficiency, pollutant generation and dispersion. Variations in temperature and relative humidity affect fuel moisture content and flame temperature, thereby regulating the formation of emissions. Similarly, wind dynamics and atmospheric stability determine the availability of oxygen and the transport of pollutants away from the kiln, which in turn alters both the magnitude of actual emissions and the concentrations observed during measurement.

The dependent variable in this study is gaseous emissions, specifically the concentrations of CO, CO₂, PM, and other gaseous pollutants emitted during the brick-firing process. This study recognizes the complexity of emissions produced from traditional brick kilns, indicating that emissions depend on the type of biomass utilized, the fuel's energy content, and the combustion process. In addition, it acknowledges the moderating influences of kiln-related external factors, facilitating a more precise analysis in Uganda's brick-making industry.

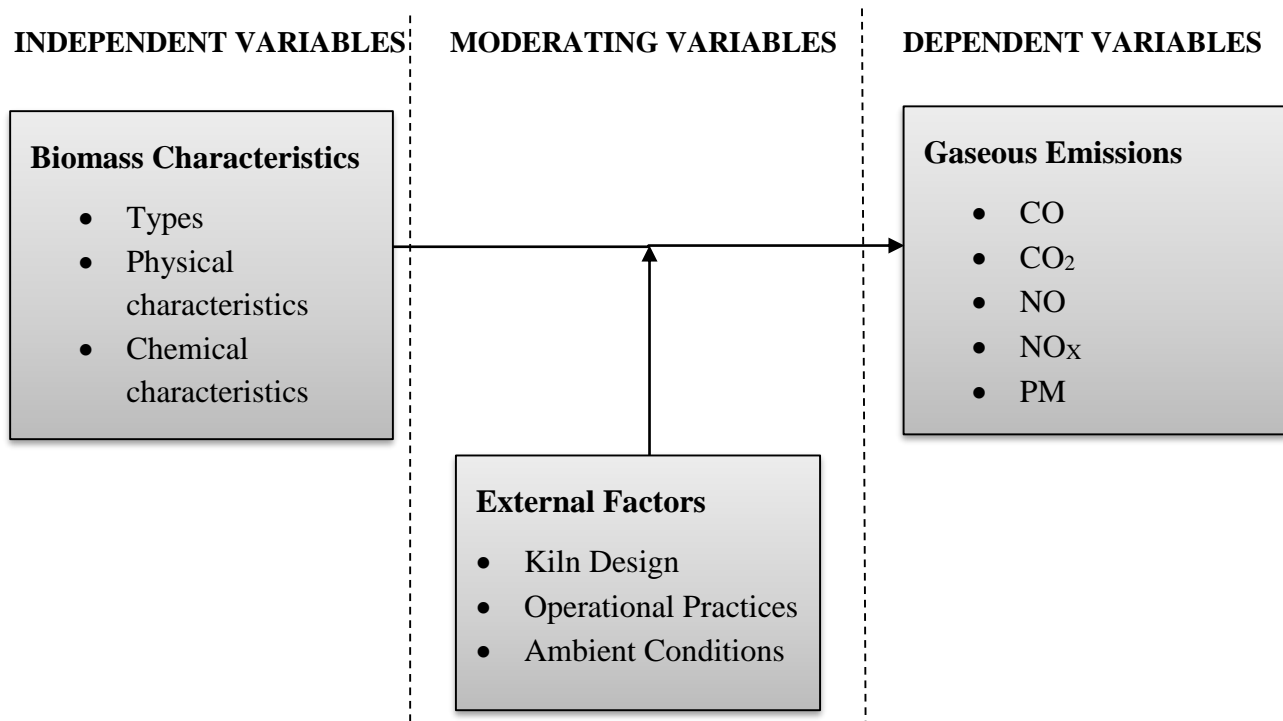


Figure 1.1: Conceptual Framework (Source; Author)

1.7 Significance

This study sought to provide knowledge about the contribution of biomass to emissions from Uganda's brick production and serve as a foundation for policy suggestions meant to encourage more environmentally friendly building methods. This research aimed to assist in providing initiative to lower the construction industry's carbon footprint and align it with Uganda's climate change mitigation objectives by highlighting the particular biomass related emission sources and possible areas for improvement. It would also propose more sustainable practices in traditional burnt brick production. By determining the characteristics of the biomass used and measuring the emissions, the study will contribute to promoting sustainable brick production practices. The insights gained could help manufacturers select biomass fuels with lower emissions, potentially encouraging the adoption of cleaner technologies or more efficient kilns.

1.8 Justification

Brick production in Uganda heavily relies on biomass as fuel, including firewood and agricultural residues. However, rudimentary kiln technologies and the unregulated use of biomass threaten the sustainability of this sector. This biomass combustion contributes to significant emissions of GHGs which degrade air quality. There are, therefore, limited data on the characteristics of biomass used and their efficiency in Uganda's brick making.

Uganda is party to many international environmental agreements, including the Paris Agreement, and has pledged in its Nationally Determined Contributions (NDCs) to mitigate greenhouse gas emissions in critical sectors such as energy and waste. Therefore, Uganda's government has made commitments to reducing GHG emissions, and the construction sector is a key contributor to the country's overall emissions. However, legislation concerning emissions from brick production are currently weak or nonexistent due to a lack of sufficient knowledge. These emissions are currently under-researched in Uganda, leaving a knowledge gap in the identification of the most polluting fuels and ways to reduce the emissions. This study aims to fill this gap by identifying the biomass characteristics that lead to higher emissions and by providing data that can inform strategies for mitigating the environmental impact.

This can further guide construction professionals like quantity surveyors, architects and brick manufacturers in Uganda towards cleaner production methods. This can be achieved through optimized fuel selection to reduce emissions.

1.9 Scope

1.9.1 Geographic Scope

The research was limited to the Greater Kampala Metropolitan Area (GKMA) in the four districts of Mukono, Mpigi, Kampala and Wakiso. This was due to the prevalence of brick making in those areas in addition to their accessibility and the availability of required data but the outcomes and findings can be applied to most areas in Uganda.

1.9.2 Academic Scope

This study was limited to the impact of biomass on gaseous emissions during burnt brick production. Biomass refers to organic material that comes from plants, which can be used as a renewable energy source. In the context of clay and mud brick production, biomass is often used as a fuel to fire the kilns which include wood, agricultural waste, and other plant materials.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter offers a comprehensive overview of existing literature on the use of biomass and the resulting emissions from traditional brick kilns. It examines studies conducted globally and regionally on brick manufacturing, focusing on the types of fuels employed, their properties, and the emissions they generate, with particular attention to the Ugandan setting. The literature review is structured around key themes that reflect the study's objectives. The chapter concludes by pinpointing significant gaps in current knowledge that this study aims to fill.

2.2 General Overview of the Brick Making Sector

On a global scale, more than 1.5 trillion bricks are manufactured worldwide yearly, predominantly in Asia and Africa, where biomass frequently serves as the principal fuel source (World Bank, 2011). Biomass fuels, including wood, sawdust and agricultural residues are largely utilized in traditional brick kilns in developing countries because of their accessibility and affordability. The traditional kilns like clamps and bull's trench kilns (BTKs), are predominant especially in rural and peri-urban environments. The burning of biomass in brick kilns is linked to inefficient combustion processes, resulting in the production of pollutants like carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), and particulate matter (PM) (Guttikunda & Goel, 2013).

The physical and chemical characteristics of biomass, such as moisture content, volatile matter, ash content, and fixed carbon, dictate its combustion efficiency in kiln conditions. McKendry (2002) states that the calorific value of biomass generally varies from 10 to 20 MJ/kg, serving as a crucial indicator of its energy potential. The moisture content is also very crucial; biomass with over 30% moisture content markedly diminishes heat production (Demirbas, 2004). These characteristics of biomass, therefore, substantially influence emissions. Low calorific value and high moisture content are recognized to diminish combustion efficiency and elevate pollutant emissions such as CO (Smith et al., 2000). All these variables interact and affect the emission profile of traditional kilns.

Traditional kilns are widely associated with inefficiency in energy utilization and environmental impacts. The IPCC (2006) indicates that these traditional kilns account for around 10% of worldwide black carbon emissions. Research conducted by Weyant et al. (2014) revealed that traditional kilns produce the highest elevated concentrations of carbon monoxide (CO) and

particulate matter (PM) in comparison to more sophisticated technologies like vertical shaft brick kilns (VSBKs) and tunnel kilns. CO₂ emissions typically arise from full combustion, whereas CO emissions are as a result of partial or incomplete combustion; both are influenced by the kind and quality of fuel used. Inadequately dried or low calorific value biomass is prone to releasing elevated levels of CO, which adversely affect air quality and exacerbate climate change. In sub-Saharan Africa, biomass continues to be the primary energy source for domestic and industrial activities, such as brick making (IEA, 2023).

Uganda's brick making industry plays a vital role in the nation's construction industry by supplying necessary building materials for both urban and rural growth. Burnt brick production methods dominate the construction sector. These methods rely heavily on biomass fuels such as firewood and crop residues which are affordable and readily accessible for many rural communities (Suleiman et al., 2021). Biomass is a renewable energy source that has been widely utilized in various industries, including brick-making. In Uganda, traditional brick kilns are among the highest contributors to industrial air pollution, yet empirical data on the specific emissions from these kilns remain scarce. Bricks baked in extremely inefficient kilns are the third-largest user of wood fuel, which is the most utilized primary fuel with an annual consumption of over 28 million tonnes of tree biomass (MEMD, 2013).

The manufacture of burnt clay bricks by traditional techniques in Uganda is associated with unsustainable biomass extraction and local air contamination. Inadequately built kilns and the utilization of wet or unrefined fuelwood lead to incomplete combustion and increased emissions of carbon monoxide and particulate matter, presenting environmental and health hazards (Okello et al., 2013). The lack of regulated kiln designs and fuel drying methods intensifies the pollution issue.

Studies conducted in South America and South Asia have established a clear link between the characteristics of biomass used and the level of emissions produced (Jayarathne et al., 2018). For example, higher moisture content and lower calorific value in biomass have been shown to lead to increased emissions due to incomplete combustion (Díez & Pérez, 2017). However, similar studies focusing on the Uganda's brick making and biomass types are limited. This gap in knowledge is critical, as the characteristics of biomass fuels can significantly influence emission levels in burnt brick production.

2.3 Brick Production in Uganda

In Uganda, brick walls, either burned or adobe, are the most commonly used building material. Compared to about 50% of homes in rural regions, over 80% of homes in metropolitan areas have brick walls (Hashemi & Cruickshank, 2015). According to Uganda Bureau of Standards (UBOS), 65% of houses in Uganda have brick walls while 32% have mud and pole walls, based on the overall distribution of households by construction material of the wall as shown in *Figure 2.1* below (UBOS, 2021).

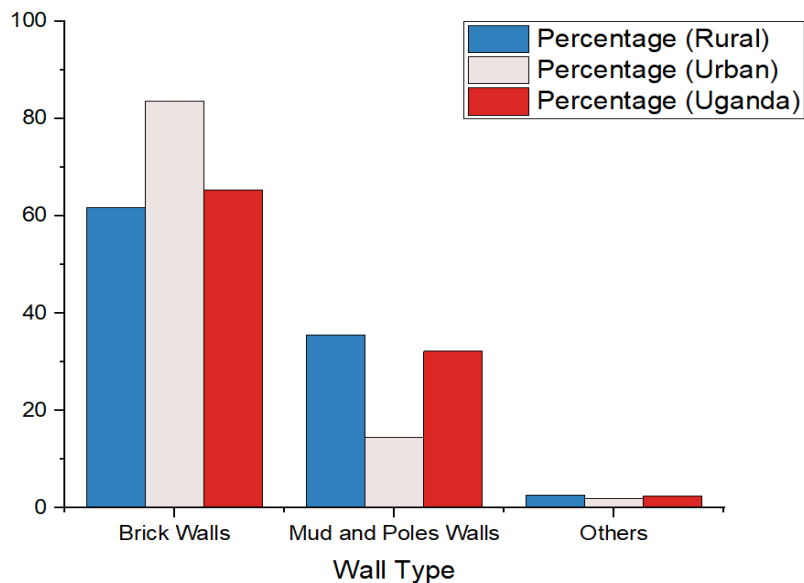


Figure 2.1: Main walling types during 2019-2020 (Source UBOS, 2021)

2.3.1 The Traditional Brick-Making Process

The brick production process is dominated by traditional clamp kilns, heavily relying on firewood and agricultural residues (Suleiman et al., 2021). The methods employed often lead to environmental degradation, including deforestation and wetland destruction, however much it provides essential building materials for housing and infrastructure (Moses Mumpembe et al., 2020). The processes involved in brick making are as follows;

2.3.1.1 Soil Extraction

The process begins with the extraction of mud or clay from wetlands and low-lying areas. This activity disrupts natural ecosystems and contributes to the degradation of wetlands and formation of borrow pits (*Figure 2.2*). This is accomplished with basic instruments or by manual kneading with the foot or knee (Aniyikaiye et al., 2021; Hashemi & Cruickshank, 2015).

2.3.1.2 Soil Preparation

At the preparation point, extracted soil is left to dry for several days to reduce moisture content. It's then sorted out by removal of hard particles like stones and grass, then manually tempered by adding water and kneading until a homogeneous mixture is achieved (Kayamba & Kwesiga, 2017).

2.3.1.3 Molding

The tempered soil is shaped into bricks using wooden molds. This hand-molding process results in bricks of varying sizes and shapes, affecting the uniformity and quality of the final product as shown in *Figure 2.2* below (UN-HABITAT, 2009).



Figure 2.2: Excavation, Preparation and Molding Processes. (a) Excavation of soil with digger and shovel; (b) Covering of the unused mortar portion to prevent evaporation; (c) Filling and levelling of mold content with shovel; (d) Inversion of mold to extrude the content; (e) Washing of mould prior to refilling with mortar; (f) Sequential arrangement of wet bricks for drying and pouring of sand on the wet bricks. (Source; Aniyikaiye et al., 2021)

2.3.1.4 Drying

Molded bricks are air-dried for several days, initially laid flat and later stood on their sides to ensure even drying. The wet bricks are covered with grass and polythene to allow coolness and air around the green bricks because direct contact with the sun causes cracks with no uniform drying (Nasly & Yassin, 2010). This step is crucial to prevent cracking during firing.

2.3.1.5 Firing

Dried bricks are stacked in clamp kilns and fired using firewood. The firing process can last anywhere from 12 up to 24 hours, consuming significant amounts of fuel especially biomass (Weyant et al., 2016). The final product is as shown in *Figure 2.3*.



Figure 2.3: Traditional brick kilns after firing (Source; Hashemi & Cruickshank, 2015)

During firing, bricks undergo a series of thermo-chemical reactions that influence both gaseous emissions and final brick properties. Initial heating drives off free and bound water, followed by the oxidation of organic matter within the brick, which generates CO_2 and, under oxygen-deficient conditions, CO and other reducing gases (Akinshipe & Kornelius, 2018). As temperature rises, carbonates such as CaCO_3 decompose (de-carbonation) to CaO and CO_2 , while subsequent reactions between CaO and silicates form new crystalline phases that contribute to strength development and vitrification (Cultrone et al., 2004). These coupled combustion and mineralogical transformations determine the in-kiln gas composition and the color, density and mechanical performance of the fired bricks.

In Uganda, traditional kilns are typically between 2.4 to 3 meters in size. The width/length of clamp kilns should not exceed 4.5 to 6 meters, despite the larger kilns' improved fuel efficiency. This is mostly because of the increased expenses, labor, and fuel consumption. For 4,000 to 10,000 bricks, the entire production process, from clay molding to the final product, takes around three weeks (Hashemi & Cruickshank, 2015).

2.4 Fuel Types Used in Brick Production

Fuels and fuel combinations used in kilns come in a broad variety. According to Weyant et al. (2016), although coal is the most popular fuel globally, brick kilns have also been found to use wood, plastic, and agricultural and industrial waste. Many kilns also use a mixture of fuels. Some fuels are pre-mixed, while others are added one at a time. Additionally, during the clay brick preparation process, fuel could be added to the clay. Ash and other low caloric fuels like agricultural residues (wheat straw and rice husk etc.) are added to clay as internal fuel to aid with the combustion efficiency. Combustion efficiency refers to the percentage of fuel energy that is effectively converted into usable heat in a combustion process, with the remainder lost as unburned gases or heat in flue gases (Khan et al., 2009). Globally, Asia is predominantly the highest producer and consumer of wood fuel, accounting for 46% of world usage as shown in *Figure 2.4*. Africa has the second highest share at 30%, followed by South America and North America, both at around 8%.

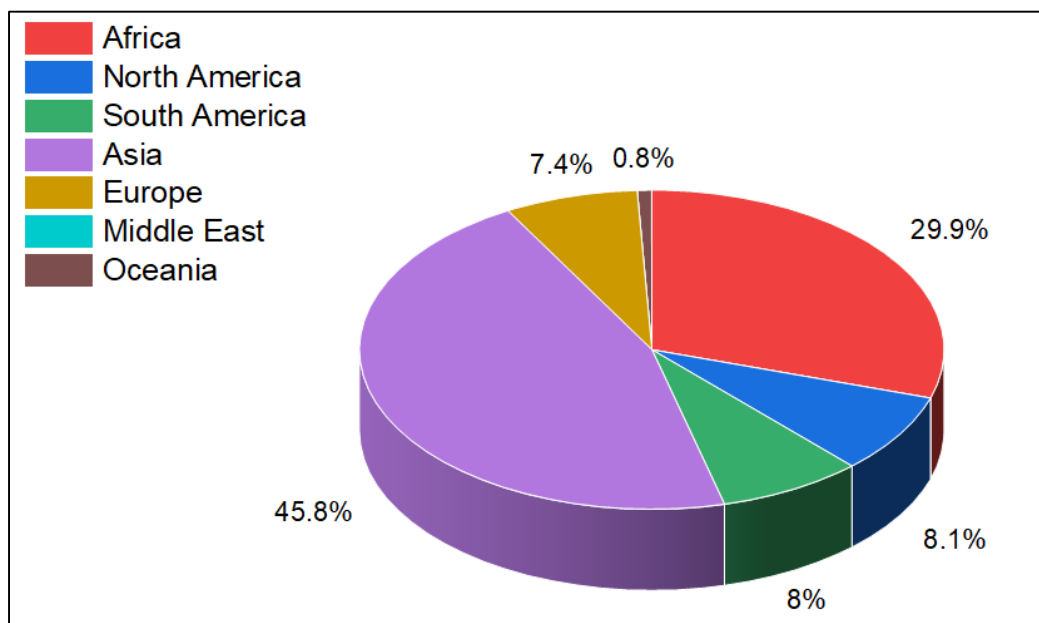


Figure 2.4: Total Regional fuelwood production (Source; World Energy Council, 2001)

Almost all countries in Africa rely on wood fuel to meet basic energy needs. According to the International Energy Agency (IEA), traditional biomass, primarily wood and charcoal, accounts for approximately 87% of Uganda’s total final energy consumption, while the African Energy Commission (AFREC) notes that traditional biomass fuels make up over 86% of Uganda’s total energy consumption, with 20% attributed to industrial use (AFREC, 2022; IEA, 2023). According to Hashemi & Cruickshank (2015), the main biomass fuels used in Uganda for burnt brick production are firewood and coffee/rice husks. *Table 2.1* summarizes the fuel types utilized in different developing countries.

Table 2.1: Attributes of bricks manufactured through traditional techniques in the developing countries (Source; Aniyikaiye et al., 2021; Kibwami et al., 2024)

Country	Types of Traditional Firing Kiln Used	Market Share from the Informal Sector	Fuel Used for Firing in Informal Sector
Botswana	Clamp	5%	fly ash, coal duff, small coal nuts
Madagascar	Scove, Bull Trench Kilns (BTK)	25%	Rice husks, agricultural wastes, peat, coal, ash, wood
Malawi	Clamp and scove	50%	Rice husks, wood Charcoal, and wood, dry leaves
Mozambique	Clamp	50%	coal, ash, charcoal, wood and farm waste.
Namibia	Clamp	NR	Charcoal and coal
South Africa	Clamp and scove	50%	fly ash or coal, wood and farm waste (macadamia husks)
Tanzania	Clamp	100%	rice husks, cotton wastes
Zambia	Clamp	10%	charcoal and wood
Zimbabwe	Clamp	12.5%	Coal, charcoal, and wood and fly ash
India	Clamp, Movable Chimney BTK, fixed Chimney BTK	NR	Biomass, coal and lignite
Uganda	Clamp	NR	Wood from locally grown trees, coffee/rice husks

Tanzania	NR	NR	Wood from locally grown trees, coffee/rice husks
Sudan	NR	<98%	Fuelwood, charcoal, agricultural residue (cotton stocks, groundnut shells, bagasse, animal dungs)
South Africa	Clamp	73%	Fuelwood, macadamia nut shell

Biomass usually refers to biological material derived from living or recently living organisms, typically used as a source of energy in the form of fuel (e.g., wood, crop residues, sawdust) (IEA, 2017). Biomass derived from agricultural leftovers in Uganda is a promising yet underexploited energy resource. Bingh (2004) indicates that leftovers from significant cash and food crops, such as banana, cassava, maize, rice, potatoes, groundnuts, coffee, and sugar cane, possess a theoretical energy potential of around 4.5TWh, or to about 4.6% of the firewood and charcoal used presently. Among all agricultural wastes, bagasse, a by-product of sugar production, stands out as the most feasible and promising due to its established technological expertise and high energy content (*Figure 2.5*). Nonetheless, other obstacles (technical, economic, and logistical) must be overcome to utilize these leftovers effectively. Enhancing garbage collecting systems, implementing reward-based incentives, and increasing processing infrastructure are essential for utilizing this potential.

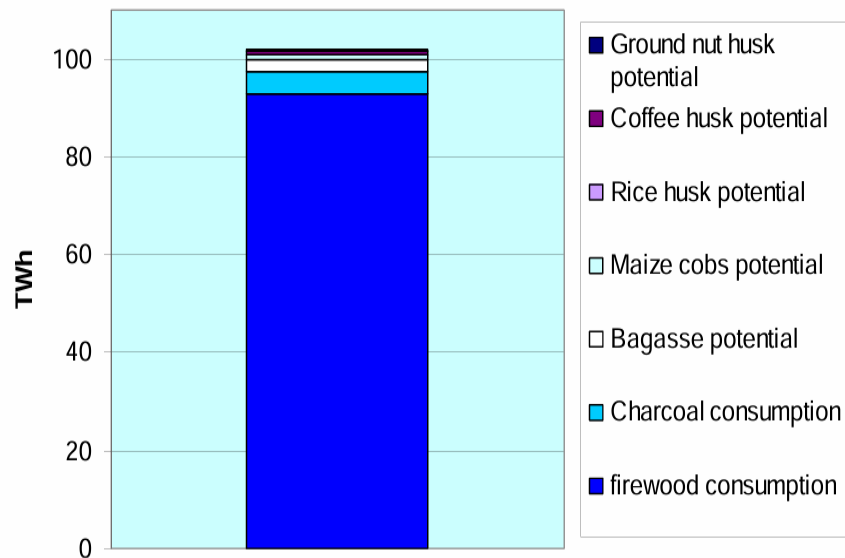


Figure 2.5: Biomass Consumption and Potential (Source; Bingham, 2004)

2.4.1 Biomass Used in Brick Production

Biomass, a renewable source of energy, consists of materials derived from plant or animal origin (Hood et al., 2013). This includes organic materials like firewood, agricultural residues, and charcoal, which are readily available and cost-effective for low-income communities. The most common form of biomass utilized in sub-Saharan African countries is wood fuel, such as charcoal or firewood (Sassen et al., 2015).

Research in other regions, especially South Asia, highlights that traditional brick kilns are among the highest contributors to industrial air pollution. For instance, studies in India and Nepal have revealed that biomass-fueled brick kilns release substantial amounts of CO₂ and particulate matter (PM), which contribute to poor air quality and climate change (Jayarathne et al., 2018). These findings are important for regions like Uganda, where traditional brick-making is widespread, but specific studies on biomass fuel types and their emissions remain limited.

In Uganda, the current need for wood fuel in the burned clay brick sector is estimated at 6 million tonnes for the traditional kilns utilized by artisan brick manufacturers and 22,000 tonnes for the pit and upgraded kilns employed by small and medium scale companies (MEMD, 2013). The data indicate that the burnt clay brick sector is the predominant consumer of wood fuel, thereby

significantly contributing to the current high rates of deforestation and emissions. The following different types of kilns utilize different biomass types in Uganda's brick making industry:

2.4.1.1 Biomass Utilization in Modern Kilns

Globally, there are many types of modern kilns used due to a wide number of advantages but that hasn't been widely adopted in Uganda. Currently, Uganda Clays Ltd. on Entebbe Road has one of the only operational Hoffmann kilns, also known as the ring kiln (Uganda Clays Limited, 2021). The Hoffmann kiln is built in a circle making it feasible to recover heat from the flue gases during combustion is the primary goal of this concept. Coffee husks are used to fire the kiln. The husks are mechanically fed into the kiln through openings in the ceiling (*Figure 2.6*). Temperature readings are taken within the kiln to control the rate at which fuel enters the combustion chambers. The temperature in the kiln is around 700°C - 900°C once the coffee husks are no longer fed (García Ubaque et al., 2010). The kiln's measurements are rather large and it fires four of its chambers every day. The capacity of these chambers is about 6,000 half bricks and this number requires fuel amounting to two 7-tonne trucks loaded with coffee husks (Bingh, 2004). These trucks' precise capacity is thought to be 3-4 tonnes of coffee husks per kiln, although it has not been tested. Temperature readings taken within the kiln control the rate at which fuel enters the combustion chambers.



Figure 2.6: Hoffmann kiln at Uganda Clays with holes in the ceiling of the kiln used to feed coffee husks into the kiln (Source; Bingh, 2004)

2.4.1.2 Biomass Utilization in Traditional Kilns

Traditional kilns may be constructed almost anywhere due to their straightforward design. These kilns are temporary, and the primary building material consists of the bricks themselves. Once the bricks are shaped using a wooden frame or manually, they are arranged in a pyramid-like structure, as seen in *Figure 2.7* below (Kayamba & Kwesiga, 2017). One or more tunnels are constructed at the foundation for the insertion of firewood, as these kilns are exclusively fueled by firewood.

During combustion, the heated flue gases ascend through the brick pyramid. Consequently, the temperature within the bricks increases sufficiently to facilitate the chemical processes occurring in them (Bingh, 2004). In rural regions, brick kilns are significantly smaller than those in peri-urban settings. Small kilns possess a greater surface-to-volume ratio, resulting in significantly elevated fuel energy intensities. According to Aniyikaiye et al. (2021), brick kilns often produce 4,000 to 6,000 bricks in rural regions, although in peri-urban places like as Mukono, kilns hold 20,000 bricks. It was determined that, on average, a 2 kg brick necessitates 1.3 kg of wood. The brick business is predicted to require 90 Peta Joules, equivalent to 6 million tonnes of wood yearly, due to significant inefficiency (MEMD, 2013).



Figure 2.7: Traditional Kiln using firewood (Source; Kayamba & Kwesiga, 2017)

2.4.2 Biomass Characteristics

Emission of gases during brick production are predominantly affected by the characteristics of the biomass. These characteristics include type, moisture content, ash content, carbon content, size. Wood accounts for 80.5% of the biomass types consumed in Uganda, followed by charcoal at 14.5% and agricultural waste at 4% (Bingh, 2004). There are two main botanical categories of wood biomass which are hardwood and softwood (Rowell, 2005).

- i. Softwoods are those woods that come from gymnosperms (mostly conifers). They are typically less dense with higher calorific value due to more lignin (26–34%) which would result in greater CO₂ emissions. Softwoods are usually needle-leaved evergreen trees such as pine (*Pinus*) and spruce (*Picea*).
- ii. Hardwoods are woods that come from angiosperms (flowering plants). They are denser with less calorific value due to less lignin (23–30%). Hardwoods are typically broadleaf, deciduous trees such as maple (*Acer*) and birch (*Betula*).

Biomass physical and chemical properties such as moisture content and calorific value, in relation to wood fuel, determine the efficiency of combustion and the quantity of pollutants emitted (Gurjar et al., 2016). Therefore, understanding the specific characteristics of biomass used in Uganda's brick kilns is essential for determining their environmental impact. The relationship between biomass properties and emissions is very essential in understanding the emissions associated with brick making. Properties like moisture content, calorific value, ash content, and elemental composition directly influence combustion efficiency and consequently, the nature and extent of emissions generated. Some of the characteristics of biomass fuel include the following;

2.4.2.1 Moisture content

The moisture content is a critical physical property affecting biomass combustion. Elevated moisture levels diminish combustion efficiency and elevate emissions, including carbon monoxide and unburned hydrocarbons (McKendry, 2002). Wood biomass generally exhibits a moisture content between 10% (air-dried) and 50% (freshly cut) (Bashir et al., 2023). It is required that all biomass be dried to 10 - 15% moisture content before firing to avoid the sharp loss of usable heat and the large increases in incomplete combustion emissions (Demirbas, 2004).

Biomass with elevated moisture content often produces increased emissions of carbon monoxide (CO) and PM, since substantial energy is first utilized to evaporate water, hence diminishing combustion temperature and efficiency (Gurjar et al., 2016). Incomplete combustion under these circumstances permits the emission of unburned hydrocarbons and soot, both of which are detrimental pollutants. On the other hand, low-moisture fuels facilitate more thorough oxidation, resulting in reduced emissions of incomplete combustion byproducts.

2.4.2.2 Calorific Value (Heating Value)

The calorific value, or heating value, denotes the energy released during complete wood combustion (Quartey et al., 2025). It is the quantity of energy liberated upon the full combustion of a certain mass of fuel, generally articulated in Mega Joules per kilogram (MJ/kg) (Kumar et al., 2015). In biomass-fueled brick kilns, calorific value (CV) is a crucial factor influencing combustion efficiency, burn temperature, and emissions production (Sivabalan et al., 2021). The Higher Heating Value (HHV) of most wood biomass varies between 18-21 MJ/kg on a dry basis (McKendry, 2002). It is affected by moisture content and the carbon to oxygen ratio. Biomass with a low calorific value requires more fuel to achieve the necessary temperatures for firing bricks, further increasing emissions.

Similarly, studies show that biomass with a lower calorific value correlates with increased specific emissions, since a greater quantity of fuel is necessary to get equivalent energy output (Demirbas, 2004). This elevates CO₂ emissions per unit of usable energy and may also result in increased black carbon emissions in traditional kilns without control mechanisms. Fuels with high calorific value like dense hardwoods, emit greater energy per kilogram and facilitate more efficient burning with less emissions (Saidur et al., 2011).

2.4.2.3 Particle Size and Shape

The size of particles influences the pace of combustion and the consistency of the heat released. According to Vamvuka (2009), smaller particles generally ignite more rapidly and thoroughly, but bigger fragments may lead to incomplete combustion. Traditional brick kilns commonly utilize uneven and unrefined biomass, which adversely impacts thermal distribution. Previous studies indicated that CO, NO_x and particulate matter emissions increased with increasing size of biomass pellets, in addition to the accumulation of ash content (Cao et al., 2011). Furthermore, the size and shape of biomass particles and excess air jointly determine the fluidization pattern and temperature

profile, thereby affecting the distribution of unburned carbon and gaseous pollutants and reducing excess air in kilns through increasing particle size results in reduced emission of NO but higher volumes of CO (Guo, 2023).

In Uganda, where brick manufacturers depend on firewood and agricultural residues, these combinations indicate that emission levels fluctuate considerably according on the chosen fuel. For instance, combining high-moisture residues with dry, high-calorific firewood may lead to more complete combustion and reduce emissions, a method already evidenced in other industries (Nanda et al., 2019). The correlation between biomass characteristics and emissions shows the significance of both the biomass type and its preparation methods, including drying, sizing, and mixing, in influencing emission results in traditional kilns.

In conclusion, while biomass combustion is widely studied for energy applications according to Hood et al. (2013), limited research focuses on its specific characteristics e.g. moisture content, calorific value in the context of burnt brick kilns. Current literature primarily examines emissions from industrial kilns or generalized biomass combustion (Amaral et al., 2014). However, there are insufficient data linking specific biomass properties to emissions in brick kilns both globally and in the Ugandan context.

2.4.2.4 Elemental composition (C, H, O, N, S)

Woody biomass (both hardwoods and softwoods) typically contains about 48–52% carbon, 5–6% hydrogen and 41–45% oxygen, with very low nitrogen (<0.5%) and Sulphur (<0.05%) on a dry, ash-free basis (Camaraza-Medina, 2025). This contrasts sharply with coal, which has higher C and much higher N and S, explaining why biomass generally produces lower SO_x and fuel-NO_x. However, the high oxygen content of biomass reduces its energy density compared with fossil fuels, which is why wood typically has HHVs of 18–21 MJ/kg (dry basis) rather than 25–30 MJ/kg as in coal (McKendry, 2002).

2.4.2.5 Volatile matter and fixed carbon

Biomass is characterized by very high volatile matter (VM) and moderate fixed carbon (FC). Forest and plantation woods often show VM of 70–80% and FC of 15–25% (dry basis), while many agricultural residues show slightly higher ash and lower FC (Jha & Dass, 2020). High volatile content gives easy ignition and rapid flame development, which is advantageous in clamp kilns where there is no sophisticated burner or forced draft. But in practice, when volatiles are

released quickly into poorly mixed, oxygen-limited flue passages, they form CO, unburned hydrocarbons and soot, raising both CO and PM emissions. Fixed carbon represents the solid char that burns more slowly and maintains kiln temperature. Studies on African agricultural residues show that higher FC correlates strongly with higher calorific value and more stable combustion, while low-FC residues (e.g. some leafy wastes) tend to smolder and smoke (Lubwama et al., 2020). In traditional Ugandan kilns, where operators continuously push wood into tunnels, fuels with adequate FC (dense hardwoods) help sustain high temperatures and more complete burnout of bricks; however, if firing is aggressive and air is restricted, even high-FC fuels still generate substantial CO because char oxidation is incomplete.

2.4.2.6 Ash content and ash composition

Ash content in wood is usually low (0.5–3% dry basis), but many agricultural residues (rice husk, coffee husk, bagasse, straw) may contain 5–20% ash, often rich in silica and alkali metals (K, Na, Ca, Mg) (Lubwama et al., 2020). High ash has several implications which include reducing the effective heating value per kilogram of fuel, because ash is incombustible ballast. Alkali- and silica-rich ashes can also cause slagging, fouling and clinker formation on hot surfaces, reducing heat transfer and forcing operators to break up fused ash mechanically (Mlonka-Mędrala et al., 2020). Mineral matter in ash can catalyze certain reactions (e.g. tar cracking, char gasification), sometimes improving burnout but also altering the distribution of pollutants (Puri et al., 2024).

2.4.3 Emissions from Biomass-Fueled Kilns

Emissions are the release of gases and particulate matter into the atmosphere as a result of chemical processes, such as combustion (IPCC, 2006). In biomass combustion, these typically include CO₂, CO, NO_x, and particulate matter (PM). Emissions from brick kilns are typically classified into two categories: GHGs such as CO₂ and air pollutants such as PM and volatile organic compounds (VOCs) (Weyant et al., 2016). Carbon footprint refers to the total amount of greenhouse gases emitted directly or indirectly by a process, measured in terms of carbon dioxide equivalent (CO_{2e}) (Wiedmann & Minx, 2007). CO and CO₂ are the principal gaseous byproducts of biomass burning. Under optimal combustion circumstances with enough oxygen, biomass is mostly transformed into CO₂ and water vapor. In situations of incomplete combustion, prevalent in traditional brick kilns due to inadequate oxygen supply, low combustion temperatures, and variable fuel moisture,

substantial quantities of CO are generated (IPCC, 2006; McKendry, 2002). Consequently, these gases constitute the predominant portion of emissions by bulk and volume.

The IPCC 2006 Guidelines and 2019 Refinement provide global benchmark emission factors and combustion efficiency indicators for CO₂, CO, CH₄, and NO_x, against which emissions from traditional kilns are commonly assessed. Studies of artisanal kilns worldwide show that clamp kilns typically exceed IPCC-implied incomplete-combustion thresholds due to high fuel moisture and poor firing control (Bhat et al., 2014; Zavala et al., 2018). Although Uganda does not set kiln-specific limits, the 2024 National Air Quality Standards and national NDC commitments offer regulatory and policy benchmarks that help contextualize emissions.

Bhat et al. (2014) found that on average, brick kilns globally emit CO of approximately 302,00 tonnes, carbon black of 6,000 tonnes, and carbon dioxide of 1.8 million tonnes. These emissions contribute to both global climate change and local air pollution. Particulate matter and CO from kilns have been significantly associated with respiratory symptoms and diseases among workers and nearby communities (Raza & Ali, 2021). In the African context, it was estimated in some studies that the total emissions from brick kilns annually were around 663,000 tonnes of CO₂, 25,300 tonnes of CO, 20 tonnes of N₂O, 720 tonnes of NO_x and 470 tonnes of NO per annum, while the total carbon released in the atmosphere would be 181,000 tonnes annually (Alam, 2006). Despite the information on the effects of these emissions, there is still lack of data for Uganda's traditional brick kilns, which should be addressed. The following are the major emissions associated with biomass fueled kilns;

2.4.3.1 Carbon monoxide

Carbon monoxide (CO) is a hazardous gas generated during burning through incomplete combustion of carbon bearing fuels (Tissari et al., 2008). Unlike carbon dioxide, which signals complete combustion, CO serves as a marker of inefficient burning. Its formation in kilns is influenced by factors such as the moisture content of the fuel, the availability of oxygen, the kiln's structural design, and how it is operated (Bhat et al., 2014). From a health standpoint, CO is highly toxic because it binds with hemoglobin, impairing the blood's ability to carry oxygen. This can lead to oxygen deficiency, particularly affecting vital organs like the brain and heart. High exposure levels may cause symptoms such as dizziness, nausea, confusion, and in extreme cases, unconsciousness or death (Weyant et al., 2016). Carbon monoxide exerts an indirect warming

effect on the environment. Carbon monoxide (CO) does not significantly absorb solar energy; rather, atmospheric processes involving CO generate greenhouse gases, ozone, and carbon dioxide (CO₂). Environmentally, CO diminishes the concentration of hydroxyl radicals (OH) in the atmosphere, so prolonging the lifespan of CH₄, a greenhouse gas that possesses a warming potential 36 times greater than that of CO₂ (IPCC, 2013).

Globally, brick kilns are major sources of CO emissions due to widespread use of outdated and inefficient technologies. Studies in Asia show that producing 1,000 bricks can generate between 6.35 and 12.3 kilograms of CO, depending on the kiln type and fuel characteristics (Bhat et al., 2014). This makes CO not only a pollutant of concern but also a useful metric for evaluating combustion efficiency. The ratio of CO to CO₂ is commonly used to assess how completely fuel is burned, with higher ratios indicating poorer combustion (Zhang & Smith, 2007).

In Uganda, brick production is dominated by clamp kilns that rely on firewood and agricultural residues, often with inconsistent moisture levels (Hashemi & Cruickshank, 2015). Although direct measurements of CO emissions are limited, field evidence suggests that inefficient combustion in these kilns leads to significant CO release, posing health risks to workers and surrounding communities. This underscores the need to include CO monitoring in emission studies, not only to understand its health impacts but also to evaluate kiln efficiency and fuel usage.

2.4.3.2 Carbon dioxide

Carbon dioxide (CO₂) is the primary emission resulting from the standard burning of carbon-based fuels, including those utilized in brick kilns (Bashir et al., 2023). It is the most prevalent and impactful greenhouse gas globally, with a climatic forcing of 1.9 Wm⁻² (Butler & Montzka, 2015). Most of the CO₂ emissions have both natural and human-made (anthropogenic) emission sources, however, increased levels of anthropogenic emissions have raised the total level of emissions above the natural absorption rates for these gases (Alam, 2006).

Brick kilns are widely acknowledged as significant industrial contributors to CO₂ emissions worldwide, especially in South Asia, where annual brick production exceeds 250 billion units (World Bank, 2011). Jayarathne et al. (2018) observed that biomass-fueled kilns in South Asia emit not only CO₂ but also notable levels of carbon monoxide, methane, and black carbon, underscoring the inefficiencies in combustion. In Latin America, artisanal kilns powered by biomass are also prevalent, though comprehensive emission data are lacking. Zavala et al. (2018) noted that CO₂ is

commonly used as a reference gas to calculate emission ratios for pollutants like CO, emphasizing its central role in combustion analysis.

Sub-Saharan Africa has limited empirical data on kiln emissions, yet biomass remains the primary energy source for brickmaking, implying significant but largely undocumented CO₂ outputs (IEA, 2023). In 2001, Africa's total CO₂ emissions stood at just 843 million metric tonnes, among the lowest globally, but the expansion of informal, biomass-dependent industries such as brick production suggests a growing impact on both regional and global emission levels (EIA, 2004). In Uganda, brick production is dominated by traditional clamp kilns that rely heavily on firewood and they emit substantial CO₂, further intensified by the calcination of clay minerals (Okello et al., 2013). Field studies in the Greater Kampala Metropolitan Area have recorded CO₂ concentrations surpassing 20,000 ppm during peak kiln operation (Suleiman et al., 2021). Although Uganda's overall greenhouse gas emissions are relatively low on the global scale, brickmaking stands out as a major emitter within the construction sector, raising concerns about sustainability and climate impact.

While CO₂ is not harmful to human health at ambient levels, its measurement is vital for evaluating the environmental footprint of brick kilns (Venkataraman et al., 2005). Additionally, the ratio of CO and other pollutants to CO₂ serves as a key indicator of combustion efficiency (Zavala et al., 2018). Although many studies assume complete carbon conversion to CO₂, traditional kilns often experience incomplete combustion, leading to higher emissions of other pollutants. This highlights the importance of CO₂ monitoring not only for climate assessments but also for improving kiln efficiency and fuel performance.

2.4.3.3 Nitrogen oxides

Nitrogen oxides (NO_x) are a category of extremely reactive gases, mainly including nitric oxide (NO) and nitrogen dioxide (NO₂), generated during the high-temperature burning of biomass (Cowling & Merrill, 1966). In traditional biomass brick kilns, NO_x emissions are affected by the nitrogen concentration in the fuel, combustion temperature, and oxygen availability (Bhat et al., 2014). Although biomass typically contains less nitrogen than fossil fuels like coal or oil, the uncontrolled firing conditions in traditional kilns marked by erratic temperatures, uneven airflow, and inconsistent fuel input can intensify NO_x generation (Guttikunda & Goel, 2013).

On a global scale, NO_x emissions from brick kilns are increasingly recognized as a serious environmental issue. In South Asia, where kilns consume large quantities of coal and biomass, NO_x significantly contributes to urban air pollution (Guttikunda & Calori, 2013). Field investigations in India and Nepal have shown that emissions from traditional kilns are high enough to trigger smog and haze, posing health risks to both workers and nearby populations (Weyant et al., 2014). Similarly, studies in Latin America reveal that artisanal kilns using biomass release notable amounts of NO and NO₂, worsened by poor kiln design and the absence of emission control systems (Zavala et al., 2018).

In Sub-Saharan Africa, research on NO_x emissions from traditional kilns is limited, despite widespread reliance on biomass for energy in both domestic and industrial contexts (IEA, 2023). Available evidence suggests that although total NO_x output may be lower than in regions dominated by coal use, inefficient combustion in artisanal kilns can still produce harmful concentrations of NO_x locally (Bond et al., 2013). In Uganda, while direct data on NO_x emissions from these kilns are scarce, regional studies on biomass combustion imply that poor firing practices likely result in measurable levels of NO and NO₂ (Okello et al., 2013). These emissions are environmentally significant due to their role in forming ground-level ozone, a major component of photochemical smog linked to respiratory issues such as asthma and reduced lung function, especially among vulnerable groups like children and the elderly (World Health Organization, 2021). NO_x also contributes to acid rain, which can degrade soil quality, hinder plant growth, and damage aquatic ecosystems in Uganda's sensitive environments (Nicolaou et al., 2023).

In conclusion, although biomass-based kilns may emit less NO_x than those fueled by coal or oil, the lack of combustion control in traditional brick kilns means that even small nitrogen inputs can result in serious air pollution. This highlights the urgent need for localized studies on NO_x emissions in Uganda to establish baseline data and inform strategies for improving kiln performance and mitigating environmental and health risks.

2.4.3.4 Particulate Matter

Particulate matter (PM) is a major contaminant resulting from incomplete combustion and suboptimal kiln designs. It comprises a blend of solid and liquid particles floating in the atmosphere, exhibiting diverse sizes and chemical compositions. The most detrimental types of particulate matter are PM_{2.5} (particles with sizes ≤ 2.5 micrometers) and PM₁₀ (≤ 10 micrometers),

which can infiltrate the respiratory system and potentially enter the bloodstream (World Health Organization, 2021). Burning biomass is a leading source of fine particulate emissions, especially when low-quality fuels like moist firewood, sawdust, and crop residues are used under oxygen deficient conditions typical of traditional kilns. Research has shown that PM_{2.5} are predominant from combustion of forest wood with levels as high as 12.35 ± 11.31 g/kg (Amaral et al., 2016). These emissions comprise soot (black carbon), ash particles, unburned organics, and mineral dust from clay which contributes to atmospheric haze, soil degradation, and climate change via the radiative forcing effects of black carbon (Bond et al., 2013; Ramanathan & Carmichael, 2008).

On a global scale, brick kilns are recognized as major sources of PM pollution. In South Asia, for instance, they emit large amounts of PM_{2.5}, intensifying urban smog and respiratory health issues (Guttikunda & Calori, 2013). In Uganda, compared to South Asia, there are limited empirical data on PM levels from traditional kilns. Hashemi and Cruickshank (2015) emphasize that Uganda's brick sector remains heavily reliant on biomass, pointing to significant particulate pollution with minimal oversight.

2.4.3.5 Black carbon

Black carbon (BC), a constituent of particulate matter, arises from the incomplete combustion of biomass (Bond et al., 2013). It possesses a significant global warming potential and contributes to local air pollution and global climate change. Biomass-fired kilns are among the primary contributors to black carbon emissions in low-income environments (Venkataraman et al., 2005). Globally, BC ranks as the second most significant driver of climate warming after CO₂, with a short-term warming potential estimated to be 460 to 1,500 times greater than CO₂ over a 20-year period (Bond et al., 2013). Unlike CO₂, which remains in the atmosphere for decades, BC has a much shorter lifespan, lasting only days to weeks, making its reduction a fast-acting strategy for improving both health and climate outcomes (Shindell et al., 2012). In regions like South Asia and Sub-Saharan Africa, biomass-fueled brick kilns are major contributors to BC emissions (Venkataraman et al., 2005). Research indicates that traditional kilns in countries such as India and China account for nearly 7% of regional BC output (Weyant et al., 2016), underscoring their relevance in climate policy. In Uganda and neighboring East African nations, heavy dependence on biomass for brick production suggests notable BC emissions, yet systematic data collection remains limited (Hashemi & Cruickshank, 2015). This lack of localized emission data from

African kilns highlights a significant research gap compared to better-documented regions like South and East Asia.

2.4.4 Emission Measurement

It is essential to quantify emissions accurately in order to comprehend how brick production affects the environment (Higazy et al., 2019). Emissions from biomass-fueled kilns can be obtained using a variety of techniques, such as portable gas analyzers that measure the amounts of CO₂, CH₄, and CO as green bricks are being burnt (Raza & Ali, 2021). Total emissions from kilns are often estimated using emission factors, which are defined as a representative value that seeks to correlate the volume of a pollutant emitted into the atmosphere with an activity linked to the emission of that pollutant (United States Environmental Protection Agency, 2024). In this case, they measure the quantity of a particular emission per unit of fuel burnt (Higazy et al., 2019). These measuring methods, which offer actual data on emissions from Uganda's brick-making kilns, are essential to the research.

2.5 Summary of The Literature Review and Research Gaps

This study's literature review shows an escalating global concern about the environmental consequences of traditional brick manufacturing, especially those utilizing biomass fuels. Research from various regions highlights that traditional kilns, particularly clamp kilns, are major contributors of air pollutants. Worldwide, there is growing emphasis on adopting cleaner kiln technologies; yet, the persistent dependence on traditional kilns in underdeveloped nations continues to be a significant area of environmental and policy investigation (Bashir et al., 2023).

Emission studies often focus on emissions associated with modern kiln technologies in Asia and South America like Bond et al. (2013) and Guttikunda & Goel (2013), however, limited attention has been given to emissions from clamp kilns commonly used in Sub-Saharan Africa, and Uganda in particular. Moreover, studies rarely measure real-time emissions under actual operating conditions. Traditional kilns, which dominate Uganda's construction sector, have unique operations and characteristics that haven't been researched. Furthermore, these studies frequently assume uniformity in biomass types, and few offer comparisons of various fuel characteristics (e.g., calorific value, moisture content) and their corresponding emission outputs. Furthermore, literature from Khan et al. (2009) primarily examines how generalized biomass affects combustion

efficiency but there are insufficient data linking specific biomass properties to emissions in brick kilns both globally and in the Ugandan context.

Most existing research and governmental publications in Uganda predominantly concentrate on the effects of firewood extraction, alterations in land use, and the overarching consequences of deforestation, while offering less consideration to the quantification of emissions from traditional brickmaking. Despite informal evidence suggesting extensive use of hardwood biomass in brick kilns, empirical data about emission levels, differences in biomass kinds, and their physical and chemical fuel qualities remain unrecorded.

This review has highlighted some critical literature gaps such as insufficient factual emission data from traditional biomass-fueled brick kilns in Uganda, especially for significant air pollutants as CO and CO₂, hindering policy formulation, planning, and emission regulation measures in Uganda's construction industry. Furthermore, there is insufficient comprehension of how biomass characteristics influence emissions in actual kiln operating settings. The identified gaps necessitate a comprehensive empirical evaluation of biomass characteristics and their correlation with emissions in traditional brick manufacturing in Uganda.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the techniques used in the investigation of emissions from traditional biomass-fueled kilns. The methodological approach of this study consists of; research design, selection of the target population, literature search, data collection and data analysis.

3.2 Research design

Research design serves as a framework for the collection, measurement, and interpretation of data, aiming to integrate relevance to the study objective with procedural efficiency. It is a conceptual structure within which research is executed (Kothari, 2004). The research employed a cross-sectional design, which entails the analysis of data gathered from a population or a representative subset at a particular moment in time (Levin, 2006). This approach was favored due to its benefit of enabling the researcher to collect data from diverse individuals, subjects, or phenomena simultaneously and at a little expense.

This research adopted a quantitative approach, by examining the relationship of biomass use and emissions in the Ugandan burnt brick-making industry. These variables, in turn, were measured, typically on instruments, so that numerical data could be analyzed using statistical procedures. Researchers can address issues like determining the components that affect a result and figuring out the best predictors of outcomes by using the quantitative method (Creswell & Creswell, 2018). This utilized field data collection, laboratory analysis, and statistical analysis.

Furthermore, the study employed a non-experimental strategy where emissions were directly measured from selected biomass-fired brick kilns within the Greater Kampala Metropolitan Area (GKMA). A non-experimental research involves studying and interpreting variables in their natural state, without the researcher intentionally changing or controlling them (Gravetter & Forzano, 2012). Unlike experimental designs, which manipulate independent variables to determine their causal effects on dependent variables, non-experimental approaches aim to describe events, explore relationships, and make conclusions based on existing circumstances (Kothari, 2004). Given the impracticality of assessing all kilns in the region, a representative sample was obtained to ensure coverage and relevance (Suresh et al., 2011). This strategy enabled the collection of reliable data under actual operating conditions, offering valuable insights into how biomass characteristics affect emissions.

3.3 Study area

The study area was the Greater Kampala Metropolitan Area (GKMA), and in relation to the brick kilns, the study was carried out in the four districts of Wakiso, Mukono, Kampala and Mpigi since they combine characteristics of urban, peri-urban, and rural areas (World Bank, 2022). Previous research noted that GKMA's large population has led to a high demand for construction materials which further creates a concentration of brick kilns, providing a representative sample for Uganda's brick production (Kasimbazi, 2018).

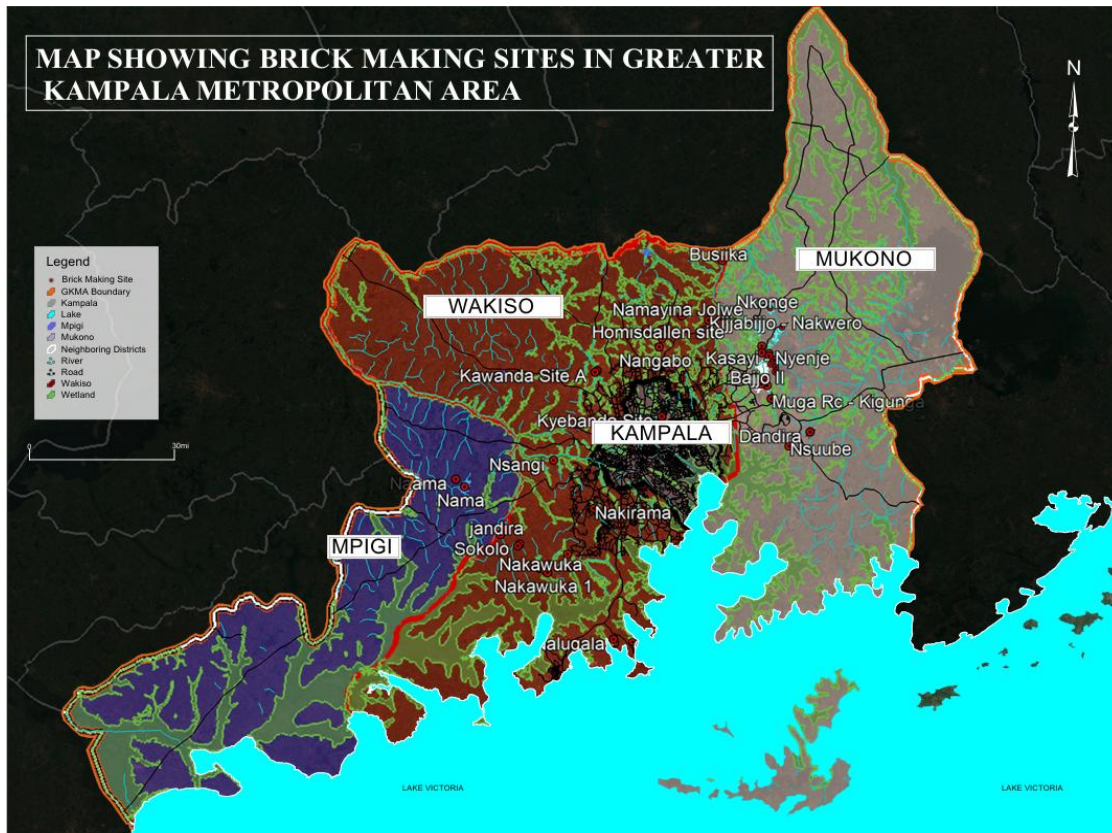


Figure 3.1: Map showing kiln distribution within GKMA

3.4 Sampling techniques and procedures

The sampling technique used in this research was purposive sampling because it involved selecting samples based on specific characteristics or criteria that are directly relevant to the research objectives (Hamed Taherdoost, 2016). This applied because the research was specifically targeting traditional brick kilns that use biomass as fuel, rather than any random kilns or other brick production methods. In addition, sampled kilns were from a specific geographic area that is GKMA (Figure 3.1) where brick-making is prevalent and where biomass is commonly used.

Criteria was used to obtain the kilns which were measured based on their ease of accessibility determined by the financial and time constraints.

3.4.1 Sample size determination

Due to the absence of a formal registry of traditional brick kilns in the GKMA, the study developed its own sample frame through field reconnaissance. A sample frame refers to the complete set or directory of all units such as individuals, items, or occurrences within a population from which a researcher draws a sample (Kothari, 2004). Since majority of clay mining and brick-making activities occur in wetlands, transect walks and google earth mapping of swampy areas were conducted across the study area (Turyahabwe et al., 2024). This identified 54 potential kiln sites, which collectively accounted for a total of 73 operational kilns (*See Appendix 8.5*). This is because certain sites were very large with potential of multiple kilns. This frame served as the basis for sample selection. Yamane's formula (*equation 3.1*) for finite populations was then used to calculate the sample size, assuming a 95% confidence level and a level of precision of 0.05 (Singh & Masuku, 2014).

$$n = \frac{N}{1 + N(e)^2} \quad (3.1)$$

Where; N is the population size

e is the level of precision

$$n = \frac{73}{1 + 73(0.05)^2}$$

A sample size of 62 kilns was determined at 95% confidence level from the frame of 73 kilns. This approach ensured statistical adequacy while maintaining logistical feasibility. However, to account for potential data loss, non-response, and operational inconsistencies, a total of 71 kilns were measured. The sample size was finally narrowed down to 63 kilns through discarding of kilns which had incomplete parameters due to equipment malfunctions during data cleaning and checks. This approach ensured that the final sample exceeded the minimum required size, thereby enhancing statistical representativeness while maintaining methodological rigor (Montgomery et al., 2021; Patton, 2015). In addition, biomass samples of hardwood type were also collected from brick-making sites. The chemical properties of each biomass type was analyzed in a laboratory to determine the calorific value, and moisture content.

3.5 Data collection methods

To address the research objectives, various data collection approaches were utilized to obtain data, obtaining a comprehensive knowledge of biomass types, combustion procedures, and emissions in traditional brick kilns. The techniques employed comprised observation, and in-situ measurements with specialized field instruments.

3.5.1 Observation

Direct observation served as a tool for documenting firsthand information on the biomass fuel types, species, and quantities employed in the brick production process. An observation checklist (*See Appendix 8.1.1*) was created to guarantee consistency and comprehensiveness of the data gathered at all kiln locations. This methodology allows the researcher to obtain direct, unobstructed insights into the actual practices of kiln operators, which is essential in naturalistic environments (Creswell & Creswell, 2018).

3.5.2 In-Situ Measurements

The study utilized in-situ measurements using a range of specialized field instrumentation to assure the precise gathering of emissions and fuel quality data from traditional burned brick kilns. The instruments were chosen for their appropriateness for field use, compatibility with kiln combustion systems, and previous validation in similar research investigations (Kothari, 2004; Montgomery, 2017). This instrumentation based method guaranteed data accuracy and uniformity across sample sites.

3.5.2.1 Emission measurements

A portable flue gas analyzer, IMR 1400 (*Figure 3.2*), was used for measuring gases such as CO₂ and CO, NO and NO_x. The analyzer was used in previous studies for quantifying emissions in brick kilns in Chile and Pakistan (Figuroa et al., 2024; Hussain et al., 2022). The IMR 1400 is a portable flue gas analyzer engineered for the measurement of combustion gases in industrial and field settings. This study employed it to obtain the concentrations of carbon monoxide (CO), carbon dioxide (CO₂), nitric oxide (NO) and nitrogen oxides (NO_x) in the emissions released from traditional clamp kilns during the brick-firing process. The analyzer was calibrated before use in accordance with the manufacturer's specifications to guarantee result dependability.



Figure 3.2: Portable Flue gas analyzer, IMR 1400 (Source; Author)

The IMR 1400 is equipped with electrochemical sensors for gases such as CO and O₂, alongside a non-dispersive infrared (NDIR) sensor for precise CO₂ measurements. It also records flue gas temperature, ambient air pressure, and O₂ content, which are critical for evaluating combustion efficiency and normalizing emission values (IMR Environmental Equipment, n.d.). Readings are presented and the device incorporates an internal data logger for result storage. The flue gas analyzer was manufactured to EN 50379 standards for portable combustion measurement and factory-calibrated with ISO-traceable reference gases. Zero and span checks using certified calibration gases were conducted before field sampling to ensure accuracy, thus improving the validity, reliability, and comparability of the emissions data collected.

In this study, scheduled kiln measurements, with continuous monitoring intervals of 30 seconds – 1 minute for approximately 2 hours per kiln, were undertaken to maximize data collection efficiency. This was on the basis of measurements of emissions from brick kilns carried out in previous studies in Chile that involved continuous measurements for 4 hours with 30-second intervals (Figueroa et al., 2024). The decision to adopt a two-hour sampling window, in contrast to the four-hour duration employed in the Chilean study, was because their kilns are relatively standardized and fewer in number, necessitating longer continuous monitoring to capture

representative data. However, clamp kilns in Uganda exhibit substantial variability and operate under open-air conditions. Prolonged monitoring at a single kiln was therefore impractical. By employing shorter sampling intervals, the study was able to encompass 63 kilns, thereby capturing a broader spectrum of combustion dynamics. This approach enhances the representativeness of the findings despite the reduced per-kiln observation period.

Although the firing process in traditional kilns typically extends over 12 - 24 hours, emission levels fluctuate considerably across different stages of the cycle. In this study, measurements were taken from kilns at distinct phases, ignition, progressive combustion, peak firing, and burnout, ensuring that, although each kiln was monitored for approximately two hours, the aggregated dataset reflect emissions across the full firing cycle.

A steel flux chamber with a chimney (*Figure 3.3*), size 1m x 1m, was fabricated and attached to the kilns, at a height of 1.5 meters from ground level, to capture representative near-source concentrations relevant to operator/community exposure while maintaining probe stability and operator safety; this height is consistent with ambient sampling guidance (1.5 - 4 m) and common field practice for low-stack, artisanal sources (Christian et al., 2019). This obtained basis from research conducted on soil emissions which utilized dome shaped flux chambers (Jentzsch et al., 2024). The results were collected directly on a laptop, in parts per million (ppm), to be further analyzed.

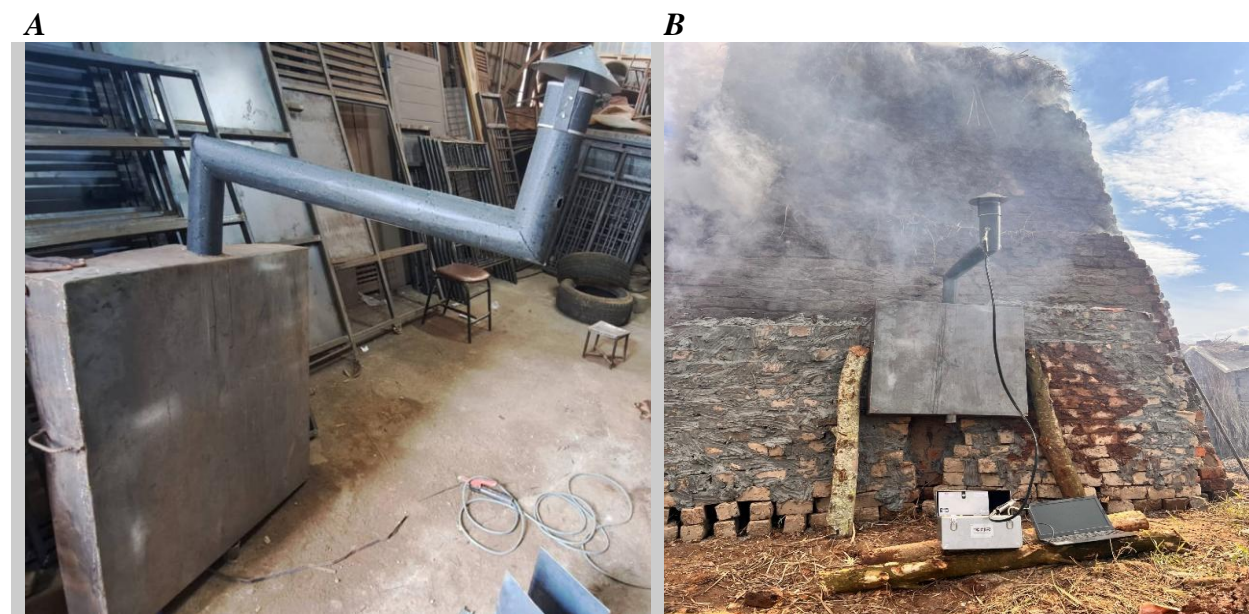


Figure 3.3: (A)- Flux chamber fabricated; (B)- Flux chamber attached to kilns (Source; Author)

3.5.2.2 *Moisture content measurements*

The moisture content of biomass was measured in the laboratory using the moisture meter (*Figure 3.4*), Testo 606-1. Previous studies indicate that the handheld moisture meters can provide equally accurate estimates of mean moisture content of wood fuel (Fridh et al., 2018). The equipment employs two sharp metal probes (electrodes) that are inserted into the wood at a uniform depth. Upon insertion of the probes, a minimal electrical current is transmitted between them (Testo SE & Co. KGaA, n.d.). Moisture is a conductor of electricity, hence, an increase in water content inside the wood results in less electrical resistance and higher moisture measurements. The device employs an internal calibration curve to translate resistance into a percentage of moisture content (% MC).



Figure 3.4: Moisture content measured using a moisture meter (Source; Author)

3.5.2.3 *Calorific Value Measurement*

Calorific value measurements were obtained using an oxygen bomb calorimeter (*Figure 3.5*), since this is the usual procedure for ascertaining the gross calorific value (GCV) of solid biomass (ASTM International, 2013; IPCC, 2006). This equipment has been used in similar studies in the assessment of the fire properties of different wood species (Quartey et al., 2025). A pre-weighed and oven-dried biomass specimen was positioned into a sealed oxygen filled combustion chamber (the "bomb") and lit electrically. The heat generated during combustion elevated the temperature

of the nearby water bath. This procedure was executed at an authorized laboratory at the Department of Mechanical Engineering at Makerere University.



Figure 3.5: Oxygen Bomb Calorimeter (Source; Author)

The energy content of the biomass was determined by calculating the temperature increase using the formula:

$$CV \left(\frac{MJ}{Kg} \right) = \frac{Q}{m} \quad (3.2)$$

Where; Q is the heat absorbed by the calorimeter and water (in joules)

m is the mass of the biomass sample (in kilograms)

3.5.2.4 Fuel amount

Fuel quantity was estimated by recording the number of elf truckloads of firewood delivered and used for each kiln; the average carrying capacity per truck was then used to convert truckloads into biomass tonnes, providing a practical and consistent estimate of fuel consumed per firing.

3.6 Data analysis

According to Creswell & Creswell (2018), there are two major types of data; quantitative data that are usually associated with numbers as the unit of analysis and qualitative data which is associated with words or images as the unit of analysis. Quantitative data analysis in this study employed descriptive and inferential statistical methods to interpret numerical information obtained from in-situ emissions measurements, calorific value assessments, and moisture content of biomass. The analysis included statistical tools, to determine patterns, compute emission factors, and investigate

correlations between biomass characteristics and emission levels. This corresponds with the positivist worldview that prioritizes objectivity and empirical measurement (Neuman, 2014).

Qualitative data, on the other hand, obtained from observations were examined using theme analysis. This entailed recognizing repeating patterns in secondary data, classifying answers, and examining the significance of the actions of kiln operators and laboratory workers (Braun & Clarke, 2006).

Before any data analysis was used to answer the research questions, the data underwent parametric tests and assumptions (Jhade et al., 2023). They assume the following;

- a. The data follow a particular distribution, usually a normal distribution,
- b. The dependent variables were continuous,
- c. The measurement scale used to be interval or ratio scale.

Due to the continuous nature of the variables and the data satisfying parametric conditions of dependent variables, parametric methods were utilized in this research.

3.6.1 Biomass Characteristics Data Analysis

For the first objective, the data obtained on biomass characteristics (*See Appendix 8.6*) were coded and then analyzed through descriptive analysis using the measures of central tendency e.g. mean, median and measures of dispersion e.g. standard deviation (Shone, 2013). The characteristics assessed included biomass type, physical properties (moisture content), chemical properties (calorific value), and fuel quantities. Data analysis was done mainly using *Microsoft Excel* and results were graphically represented using *OriginPro 2024*. The analysis was as outlined below:

3.6.1.1 Biomass Types

The biomass species used as kiln fuels were obtained from observation checklists and categorized. Frequencies and percentages were computed to determine the prevalence of each species across the 63 kilns and represented with figures. They were then compared against established classifications from the literature.

3.6.1.2 Moisture Content

Descriptive statistics were calculated to summarize moisture variability across all kilns. The data were further disaggregated into three firing periods to capture changes in moisture of wood over time.

3.6.1.3 Calorific Value

Descriptive analysis was carried out and similar to moisture analysis, calorific values were examined across three firing periods to capture changes in fuel energy quality.

3.6.1.4 Fuel Quantities

Fuel usage (in tonnes) was summarized using descriptive statistics. The range, mean, and standard deviation of fuel consumed per kiln were computed. Comparative analysis was conducted against benchmarks from prior studies. Finally, inferential statistical methods were applied to examine interactions between biomass properties that is moisture content and calorific value, fuel quantity and moisture content and finally fuel quantity and calorific value. A linear regression analysis tested the association between the properties. Scatter plots with regression lines were used to illustrate these relationships.

3.6.2 Emission Data Analysis

3.6.2.1 Gaseous Emissions

To fulfill the second objective, the emission data collected (*See Appendix 8.6*) were first cleaned, organized and then combined with the data collected above and only complete checklists were considered for analysis. After cleaning, the kilns were coded and entered into the computer. The data obtained on emissions were then analyzed through descriptive analysis using the measures of central tendency. Data analysis was done using *Stata software (version 19)*, *Microsoft Excel* and *OriginPro 2024* in a manner that they can answer the research objective. The flue gas analyzer first reported carbon dioxide concentrations in percentage units (%). To ensure alignment with emission reporting regulations and for statistical comparison with other pollutants like CO (measured in ppm), the CO₂ values were converted to ppm using the formula;

$$CO_2(ppm) = CO_2(\%) \times 10,000 \quad (3.3)$$

Where:

- CO₂ is Carbon Dioxide

This standard conversion is based on the definition of ppm as parts per million by volume (ISO 4219:2022). Previous studies on brick kilns in Australian have measured and analyzed emissions using the same units (Ukwatta et al., 2018). The emission data were then compared across different kilns to analyze the impact of biomass characteristics on emissions. To assess the evolution of

emissions over the firing cycle, emission concentrations were disaggregated into three 8-hour periods (0 - 8 hours, 8 - 16 hours, and 16 - 24 hours), consistent with procedures in biomass combustion research (Weyant et al., 2016). This allowed for comparison of variability between ignition, stable burning, and burnout phases. Time-series plots were also generated to examine trends in ppm concentrations throughout the kiln cycle.

This study reconstructed full-cycle emission profiles by pooling short continuous measurements of approximately 2 hours taken at different data points across multiple kilns. This distributed/composite sampling approach is consistent with established brick-kiln field protocols that recommend sampling many representative firings and combining time-limited traces to characterize kiln emission behavior when long continuous monitoring of every kiln is infeasible (Thompson et al., 2016).

3.6.2.2 Conversion of Concentrations to Emission Factors

The carbon mass balance approach was employed to calculate the emission factors of the pollutants in the research. The primary assumption for this approach was that all carbon content in the fuel was released as carbonaceous gases, specifically CO₂ and CO (Adhikari et al., 2019; Stockwell et al., 2016). However, due to significant variability in the fuel or fuel mixtures utilized across different kilns, as well as discrepancies in brick production among these kilns, potentially affecting carbon content and gross calorific value, fluctuations in all the aforementioned parameters might readily induce a degree of uncertainty in the emission estimations. To address these issues and enhance measurement accuracy, it is necessary to augment the quantity of kiln measurements, which may be regarded as an additional scope of the study (Nepal et al., 2019). The emission factors of CO and CO₂, expressed as grams of pollutant per kilogram of wood fuel burned (g/kg), were computed as follows:

$$EF_{CO}(gkg^{-1}) = \frac{c_{CO}}{TC} \times F_C \times m_{CO} \times 1000 \quad (3.4)$$

$$EF_{CO_2}(gkg^{-1}) = \frac{c_{CO_2}}{TC} \times F_C \times m_{CO_2} \times 1000 \quad (3.5)$$

where:

cCO = carbon content in CO (kg C/kg fuel),

c_{CO_2} = carbon content in CO_2 (kg C/kg fuel),

TC = Total Carbon.

F_c = carbon weight fraction = 0.5 for air dried wood

m_{CO} = molecular carbon fraction of CO = $12/28=0.4286$,

m_{CO_2} = molecular carbon fraction of CO_2 = $12/44=0.2727$.

This conversion allowed the derivation of fuel-based emission factors (EF_{fuel}), reported as grams of pollutant per kilogram of biomass burned for further comparison to determine if they differed significantly with prior studies documented in other regions (IPCC, 2006).

3.6.3 Biomass and Emission Relationship

To address the third objective, statistical analyses that is descriptive and inferential were conducted so as to identify and examine relationships between data on biomass characteristics and emissions data. Biomass characteristics and emissions were measured using distinct instruments but rendered directly comparable through kiln-level linkage. Biomass samples were analyzed in the laboratory to determine moisture content and calorific value, while emissions were recorded in-situ during firing. These paired datasets were merged by kiln ID, enabling statistical evaluation of the relationship between fuel quality and emission behavior. Specifically, the entry and analysis of data were done using *Stata software (version 19)*, *Microsoft Excel* and *OriginPro 2024* in a manner that they can answer the research objective. The main statistical procedures employed were Pearson correlation analysis (r) and Linear Regression analysis;

Pearson's correlation coefficient (r) was calculated to analyze the strength of the linear relationships between properties of biomass (moisture content, calorific value) and emissions (concentrations of CO and CO_2). This was employed due to the continuous nature of the variables and its widespread application in environmental and energy-related research (Field, 2018). This analysis examined the relationships between several biomass characteristics and emissions.

The regression model was used to evaluate the predictive relationship between an independent biomass variable (calorific value, moisture content) and the dependent variables (CO and CO_2 emissions). Regression analysis was chosen for its ability to evaluate both statistical significance and the proportion of variance in emissions

attributable to fuel properties (Montgomery et al., 2021). Separate models were constructed for each gas type, incorporating biomass characteristics as independent variables to indicate the direction and strength of relationships. The coefficient of determination (R^2) was used to gauge the explanatory power of each model. The following is a formula for linear regression:

$$Y = \beta_0 + \beta_1 x_1 + \varepsilon \quad (3.6)$$

Where:

- Y is the dependent variable e.g. emission level (either CO or CO₂)
- x_1 is the independent variable e.g. biomass characteristics (e.g., calorific value, moisture content)
- β_0 is the intercept (value of Y when $x = 0$)
- β_1 is the slope coefficient (rate of change of Y per unit change in x)
- ε is the error term

By integrating correlation and regression analyses, the study effectively identified both the presence and magnitude of relationships between biomass characteristics and kiln emissions. This dual-method approach is consistent with established practices in bioenergy and combustion research, where statistical modeling is frequently employed to elucidate the influence of fuel properties on emission behavior (Demirbas, 2004; Obernberger & Thek, 2004).

3.7 Validity and Reliability

Ensuring validity and reliability was integral to the study's methodological framework, aimed at producing credible and replicable findings on biomass properties and emissions from traditional brick kilns. Validity refers to the extent to which the methods used accurately measure the intended variables, while reliability relates to the consistency of the measurements under repeated conditions (Creswell & Creswell, 2018). Validity was addressed through standardized measurement protocols. Biomass characteristics were captured following Standard Test Methods for Analysis of Wood Fuels (ASTM) guidelines. Emissions were measured in the field using a calibrated flue gas analyzer, a method widely recognized for its accuracy in combustion studies. In addition, biomass and emission samples collected were from different districts in GKMA to

ensure representativeness. The regression diagnostics confirmed the models' statistical validity, ensuring that the reported emission factors and relationships are empirically robust, methodologically sound, and reflective of actual kiln performance rather than assumptions or instrumentation.

Reliability was ensured through continuous sampling procedures and repeated measurements. Biomass samples were handled uniformly to prevent contamination, while emissions were recorded at standardized intervals using the same equipment across all sites. This diversity in context enhances the applicability of the results beyond individual kiln sites (Yin, 2018). Finally, validity and reliability of the regression model was achieved by testing it against data collected from additional kilns or repeated measurements.

3.8 Ethical considerations

Research ethics encompass the principles that ensure scholarly work is conducted with integrity, respect for participants, and protection from harm (Resnik, 2018). This study considered many ethical factors to guarantee adherence to institutional mandates and overarching research ethics standards. The primary ethical issues included:

- a. Gaining informed consent from participants and ensuring data anonymity.
- b. Plagiarism especially when using secondary materials.

The first issue was addressed as through obtaining Letters of introduction were from the Head of Construction Economics and Management Department at Makerere University to be presented to all parties that will be party to this research (*See Appendix 8.2*). In addition, verbal informed consent was requested to ensure kiln operators understand the purpose and confidentiality of the research before data collection. Data confidentiality was maintained throughout all phases of the study procedure. All identifying information on kiln owners was omitted with each kiln designated a unique code instead of its actual name in the dataset.

The second issue was addressed through acknowledgment of authors of existing literature to avoid plagiarism. Academic integrity was upheld through proper citation and referencing of all secondary sources, ensuring originality and compliance with APA standards (American Psychological Association, 2020).

3.9 Limitations

- i. There were challenges of moving the one portable gas analyzer systematically between sites while planning data collection to ensure kiln measurements align with their operational schedules.
- ii. In addition, due to the temporary nature of the clamp kilns, scheduling of measurements was difficult since the firing is heavily reliant on conditions like weather which affects planning.
- iii. There was also challenge of remote sites that are not easily accessible and were problematic when transporting the gas analyzer.

To mitigate the impact of methodological limitations, equipment limitations were managed by focusing the study on gaseous pollutants and maintaining strict calibration and uniform use of the analyzer. Furthermore, the fabricated flux chamber was made detachable to ease transportation and use of motorcycles to remote kilns. A large, geographically distributed sample enhanced generalizability, while potential inaccuracies in fuel quantities were mitigated through field-based verification methods. These measures collectively ensured the reliability of the study despite unavoidable limitations.

3.10 Summary

The chapter above shows the methodological approach to be followed including the study area, sampling, data collection techniques, data analysis techniques, validity and reliability of the research instrument and the ethical considerations emphasizing how all the major parts of the research study worked together in an attempt to answer the research question.

CHAPTER FOUR: RESULTS

4.1 Introduction

This chapter focuses on presenting the results so as to answer the main objective of the study which was to assess the impact of biomass on gaseous emissions from traditional brick kilns in the Ugandan construction sector. The chapter presents a brief distribution of the total kilns from which emissions were measured in this study. This is followed by the presentation of the findings as per the objectives of the study by: characterizing the biomass used in traditional brick kilns, determining the emissions from biomass-fueled traditional brick kilns and determining the influence of biomass characteristics on emissions from traditional brick kilns.

4.2 Characteristics of Biomass used in Traditional Brick Kilns

For the first objective, the study aimed to determine the different characteristics of biomass used in the traditional brick kilns by type, physical properties and chemical properties. These were obtained from the observation checklists and in-situ measurements. The study involved emissions monitoring from 63 traditional kilns which were obtained from the GKMA; with Wakiso district exhibiting the highest number of kilns, 42, followed by Mukono with 17 kilns, Mpigi with 2 kilns and finally Kampala with 2 kilns. *Figure 4.1* shows a summary of the distribution of kilns within districts from which the study kilns were obtained.

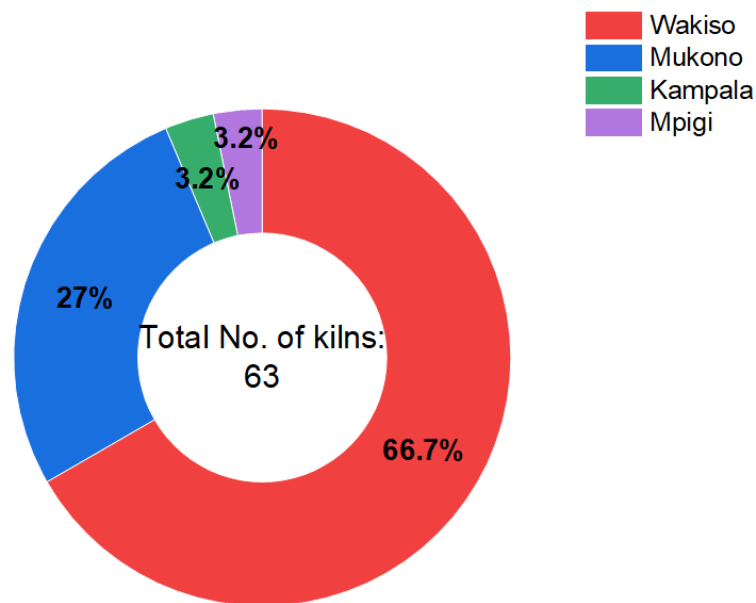


Figure 4.1: Distribution of Kilns within the Study Area (Source; Primary Data)

4.2.1 Biomass types

The research findings from this study indicate that there is only one type of biomass used as fuel for these 63 traditional kilns, that is, hardwood. The hardwood used was in a variety of species as shown in *Figure 4.2*. These were utilized either individually or in combinations.

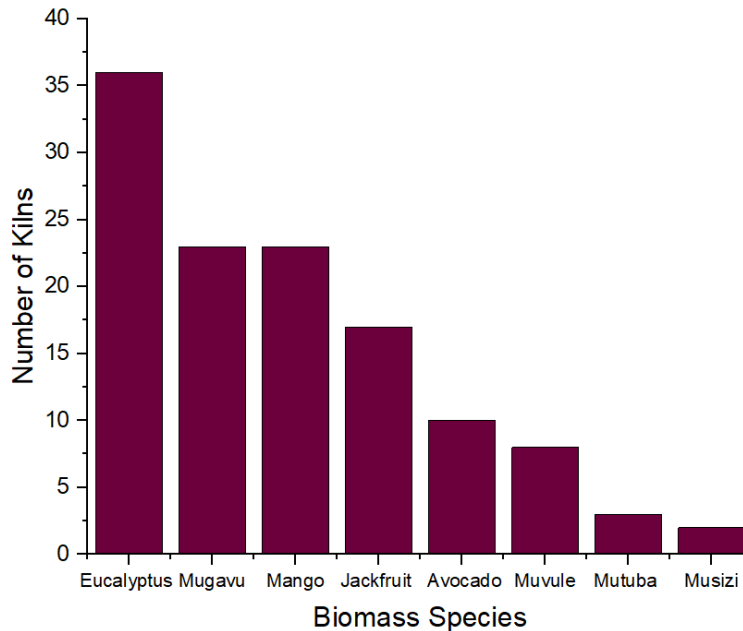


Figure 4.2: Biomass Hardwood Species Utilized in the Kilns (Source; Primary Data)

Two species emerged as the primary or exclusive fuels that is eucalyptus and mugavu. Eucalyptus served as the only or principal fuel in thirty-six (36) kilns. Mugavu is utilized exclusively or predominantly in twenty-three (23) kilns. The other species were mostly utilized in conjunction with others for example mango, locally known as muyembe, was employed in twenty-three (23) kilns in a blended pattern. Jackfruit, locally known as fene, was utilized in seventeen (17) kilns while avocado was used in ten (10) kilns. Muvule was found in only eight (8) kilns and in a mixed condition. Mutuba was utilized in just three (3) kilns while Musizi was used in two (2) kilns.

4.2.2 Moisture content

The physical property of biomass ascertained for this study was moisture content due to its impact on the combustion of biomass. This was obtained for samples of hardwood used in all 63 kilns using a moisture meter and the results were ranging between 11.86 -17.44%. Descriptive analysis indicated that the mean moisture content is $15.5 \pm 1.43\%$. The moisture content was approximately normally distributed as indicated in *Figure 4.3*, exhibiting no significant outliers. This further

shows that the moisture level of the majority of biomass samples ranged from 15% to 17%, with 15% being the most common. Extremely wet samples (18%) were less frequent but still present while very dry samples (less than 13%) were uncommon.

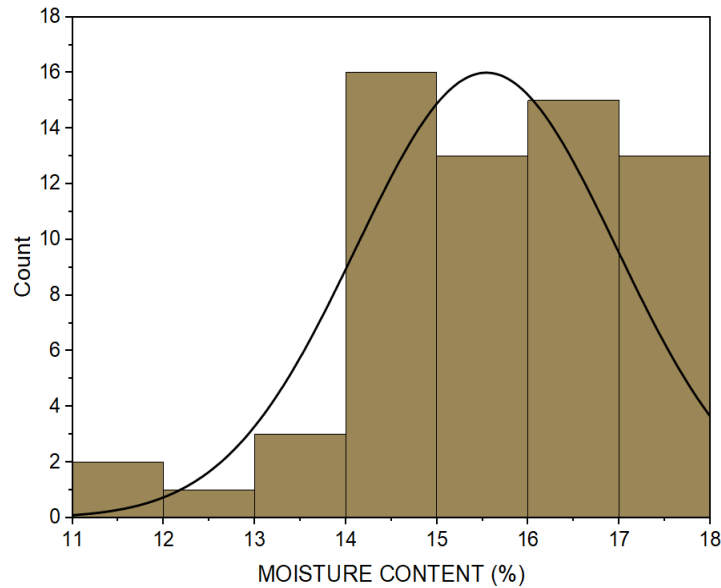


Figure 4.3: Moisture Content Distribution in Monitored Kilns (Source; Primary Data)

The study further analyzed the moisture content over the entire burning cycle. This involved splitting the entire burning cycle into three burning periods that is Period 1 which is 0 – 8th hour, Period 2 which is 8th -16th hour and P3 which is 16th – 24th hour as shown in *Figure 4.4*.

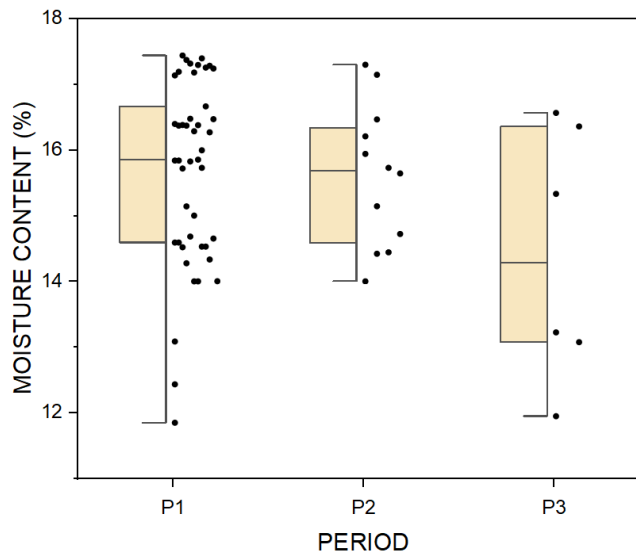


Figure 4.4: Moisture Content over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Primary Data)

In the first period, the median moisture level was about 15.8%, with a broad interquartile range (IQR) and clear outliers at both ends (11.8% and 17.5%). In Period 2, the median went down a little to about 15.6%, and the IQR was narrower. The median moisture content went further down to around 14.2% by Period 3.

4.2.3 Calorific Value

The calorific value (MJ/Kg) of all 63 samples was obtained and ranged between 11.2 -26.4MJ/Kg. Descriptive analysis indicated that the mean calorific value is 18.25 ± 3.64 MJ/Kg. The calorific value had an approximate normal distribution, as seen by the histogram shape *Figure 4.5*. This further showed that the calorific value of the majority of biomass samples ranged from 20 to 22 MJ/Kg, with 20MJ/Kg being the most common. Extremely high and low calorific values were less frequent but still present.

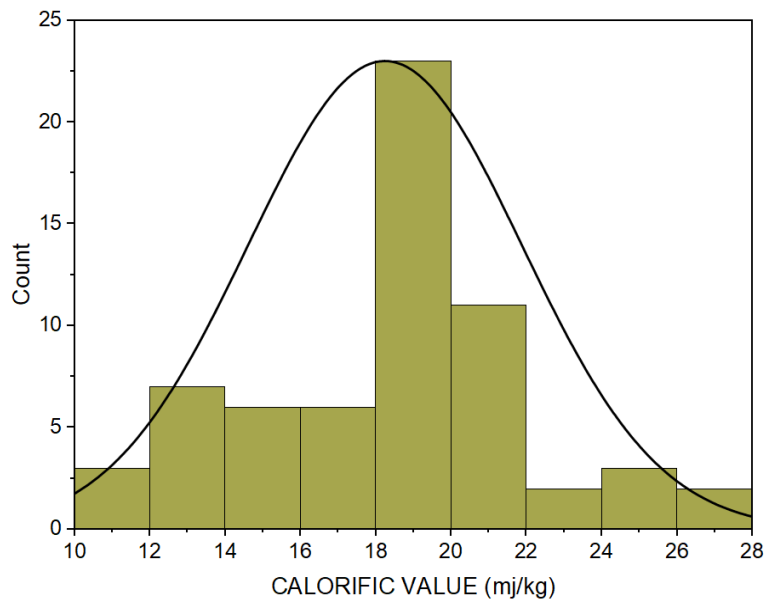


Figure 4.5: Calorific Value Distribution in Monitored Kilns (Source; Primary Data)

Similarly, the calorific value of biomass fuels was analyzed along the entire 24-hour cycle in three 8-hour periods as shown in *Figure 4.6*.

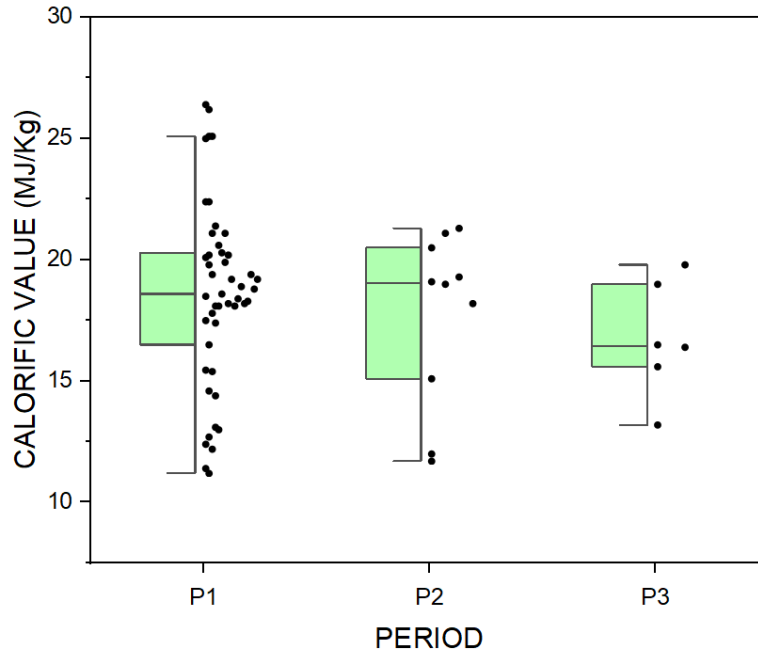


Figure 4.6: Calorific Value over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Primary Data)

In the first period, the median calorific value was roughly 18 MJ/kg with a broad IQR. The median calorific value rose slightly to around 19 MJ/kg in the second period, while the interquartile range, approximately 15 - 20 MJ/kg, became substantially smaller. During this time, almost all fuels went beyond 18 MJ/kg, which means they burned more efficiently and produced less pollution. Period 2 shows a considerable improvement in energy quality and consistency compared to Period 1. The third period saw a drop, with the median CV dropping to about 16.5 MJ/kg and most values falling between 12.5 and 20 MJ/kg.

4.2.4 Fuel Quantity

The histogram (*Figure 4.7*) shows the allocation of fuel quantities utilized among the measured traditional brick kilns which ranged from 2.3 – 12.65 tonnes. Descriptive analysis indicated that the mean calorific value is 7.17 ± 2.89 tonnes. The histogram indicates that the majority of kiln firings utilized 6 tonnes of fuel, based on the number of bricks being burnt.

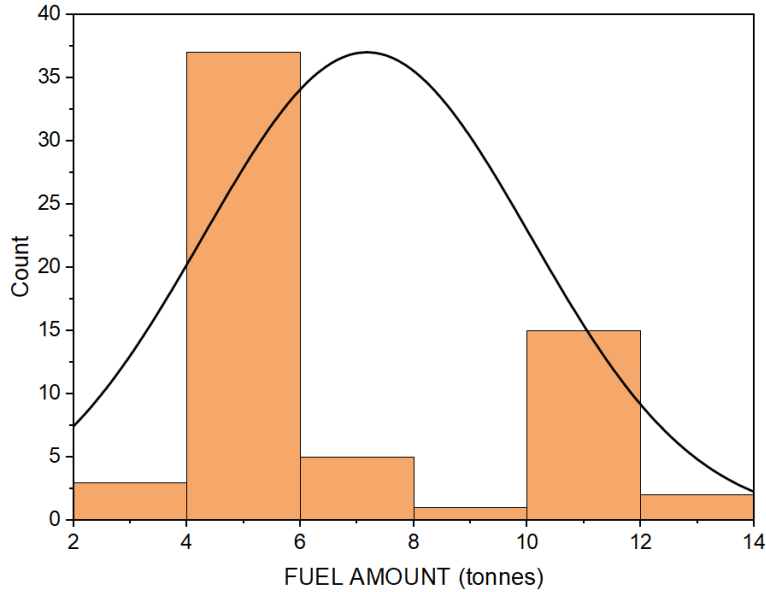


Figure 4.7: Fuel distribution in Monitored Kilns (Source; Author)

There were fewer kilns that utilized fuel at the extremes of the histogram, with some utilizing as little as 2-3 tonnes and others necessitating as much as 10-12 tonnes, while a few exceptional instances documented up to 14 tonnes. The fitted curve demonstrates a slightly right-skewed distribution, with the majority of observations concentrated in the lower to mid-range, while a smaller number of kilns are found in the higher fuel consumption categories.

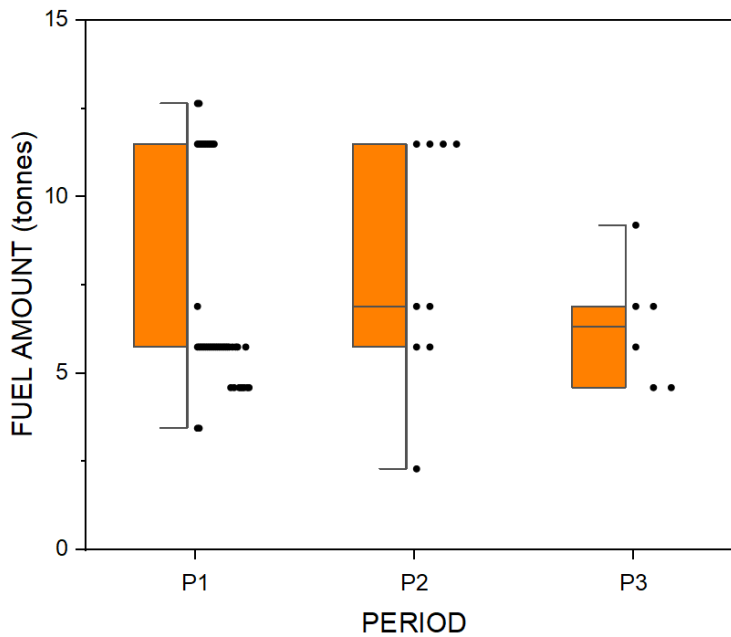


Figure 4.8: Fuel used over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Primary Data)

The boxplot (*Figure 4.8*) above indicates fuel quantities throughout three firing periods (P1, P2, and P3). During Periods 1 and 2, median consumption fluctuated between 6 and 8 tonnes, nevertheless, the interquartile ranges were extensive, and several outliers were identified. Period 3 had a more restricted interquartile range, and a reduced number of extreme outliers. This indicates a transition towards enhanced consistency and a marginal decrease in fuel consumption during the latter firing cycle. The two figures above both demonstrate that biomass use in the tested traditional kilns varies significantly among operators, with total usage ranging from 2 to 14 tonnes, predominantly relying on 4 - 6 tonnes each cycle depending on the number of bricks to be burnt. Furthermore, for the total of approximately 1.15 million bricks burnt in the 63 kilns studies, the amount of biomass wood fuel required to fire 1000 bricks was found to be 330kg.

4.2.5 Moisture content and calorific value of biomass

The study sought to assess the impact of biomass properties on emissions and the link between moisture and calorific value is a fundamental process. A negative association was noted between moisture content and calorific value as shown in the scatter plot in *Figure 4.9*. Biomass with higher moisture content needs additional energy to vaporize water during burning, thereby diminishing its net calorific value.

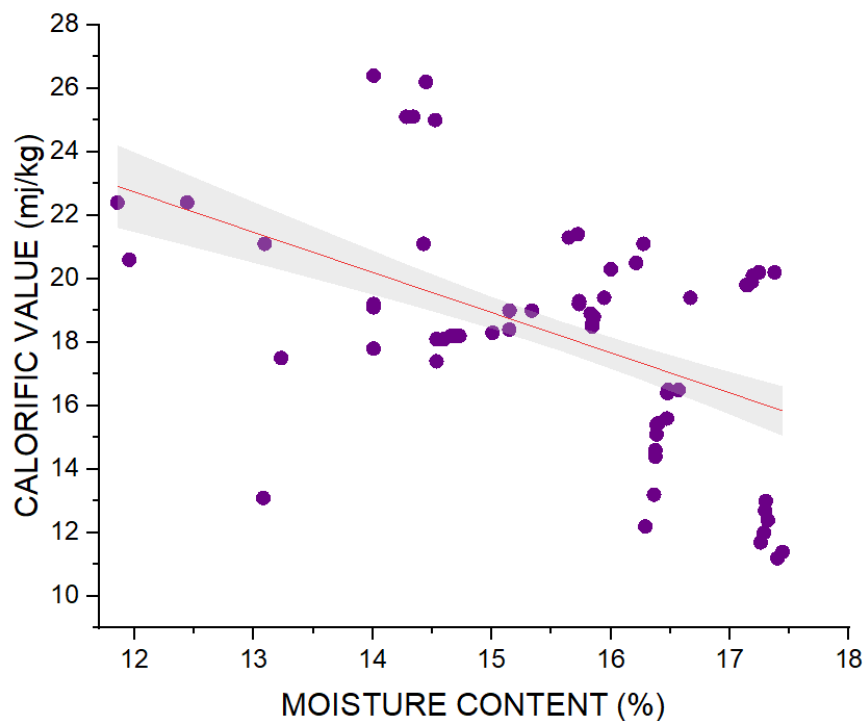


Figure 4.9: Moisture Content And Calorific Value (Source; Primary Data)

Regression analysis indicated a statistically significant negative correlation between biomass moisture content and calorific value, $F(1, 61) = 20.02$, $p < 0.0001$. The output (*Table 4.1*) accounted for around 24.7% of the variation in calorific value ($R^2 = 0.25$).

Table 4.1: Regression Output for Moisture Content and Calorific Value (Source; Author)

Calorific Value	Coefficient	Constant	P-value	R ²
Moisture Content	-1.26	37.90	0.000	0.247

The findings demonstrated that for each 1% rise in moisture content, the calorific value diminished by approximately 1.26 MJ/kg ($\beta = -1.26$, $p < 0.0001$, 95%). The linear regression equation is:

$$\text{Calorific Value(MJ/Kg)} = 37.90 - 1.26 \times \text{Moisture Content (\%)} \quad (4.1)$$

4.2.6 Fuel quantity and moisture content of biomass

Further analysis sought to assess the influence of fuel quantity on moisture content of biomass fuel. A negative association was noted between fuel quantity used and moisture content of the fuel as shown in the scatter plot in *Figure 4.10*. The scatter plot indicates that greater biomass use correlates with a marginal decrease in moisture content.

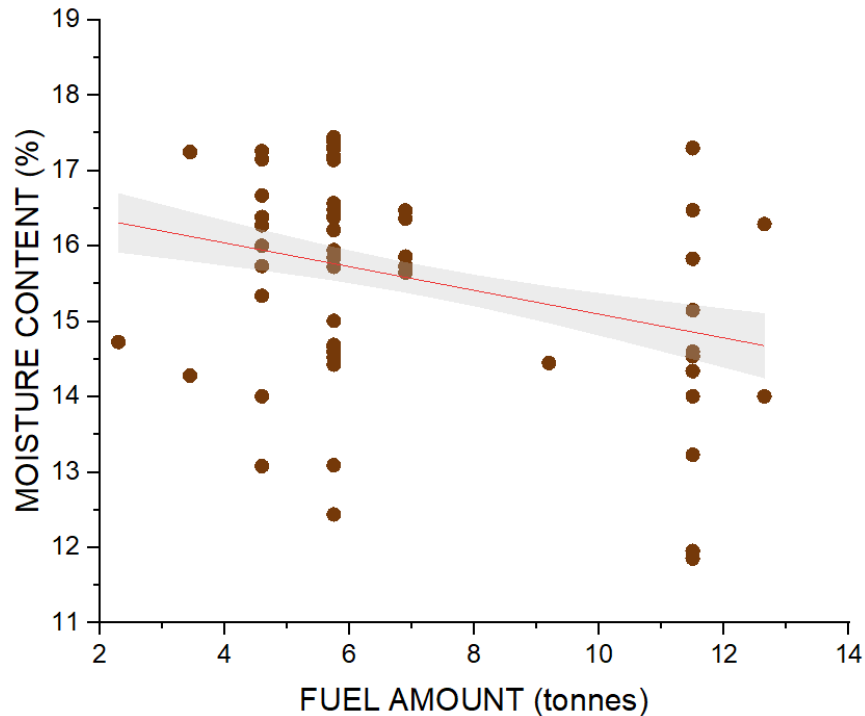


Figure 4.10: Fuel Amount and Moisture Content (Source; Primary Data)

This tendency aligns with the regression findings (*Table 4.2*), which revealed a statistically significant negative coefficient ($\beta = -0.16$, $p = 0.011$). The fitted regression line indicates that for every extra ton of fuel consumed, the average moisture content diminishes by around 0.16%.

Table 4.2: Regression Output for Fuel Quantity and Moisture Content (Source; Author)

Moisture Content	Coefficient	Constant	P-value	R ²
Fuel amount	-0.16	16.67	0.011	0.10

However, the R^2 value highlights that the quantity of fuel accounts for just a little fraction (10%) of the overall change in moisture content. The linear regression model is:

$$\text{Moisture Content}(\%) = 16.67 - 0.16 \times \text{Fuel amount (t)} \quad (4.2)$$

4.2.7 Fuel quantity and calorific value of biomass

The scatter plot (*Figure 4.11*) indicates no major relationship between fuel quantity of biomass and calorific value.

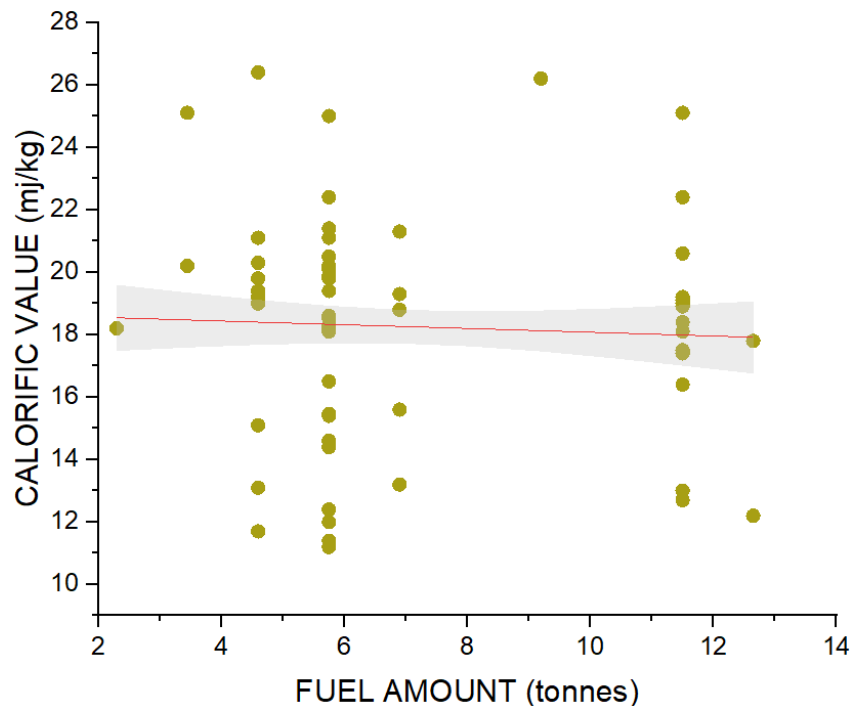


Figure 4.11: Fuel Amount and Calorific Value (Source; Primary Data)

A linear regression analysis was performed to investigate the correlation between fuel quantity (in tonnes) and the calorific value of the biomass. The output (*Table 4.3*) lacked statistical

significance, $F(1, 61) = 0.14$, $p = 0.71$. The coefficient of determination ($R^2 = 0.0023$) indicated that the fuel amount accounted for less than 1% of the variance in calorific value.

Table 4.3: Regression Output for Fuel Quantity and Calorific Value (Source; Author)

Calorific Value	Coefficient	Constant	P-value	R ²
Fuel amount	-0.06	18.68	0.708	0.0023

4.3 Emissions from Biomass Fueled Brick Kilns

4.3.1 Gaseous Emissions

For the second objective, the study aimed to determine the emissions associated with the biomass used in traditional brick kilns. This section provides the findings on the different emissions associated with the biomass fuel in the traditional brick kilns. The major emissions obtained from the field data include; carbon monoxide (CO), carbon dioxide (CO₂), Nitric Oxide (NO), Nitrogen oxides (NO_x) as illustrated in *Figure 4.12*.

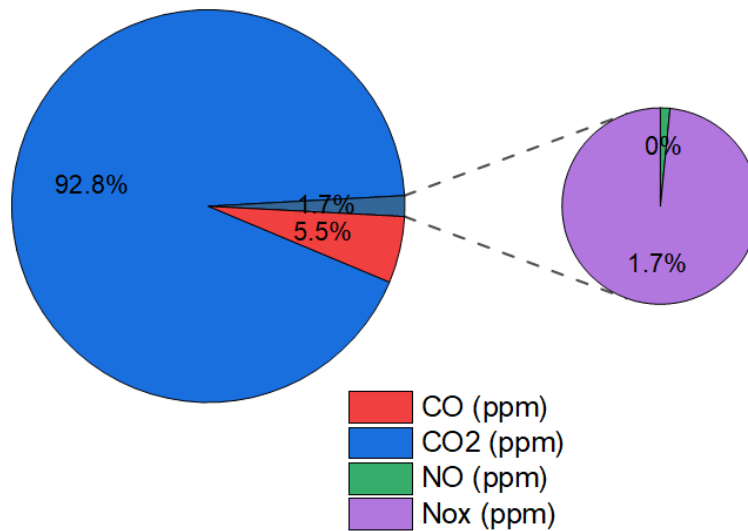


Figure 4.12: Distribution of mean emission concentrations (Source; Primary Data)

Carbon dioxide (CO₂) exhibited the greatest concentrations among the studied emissions, averaging 92.8%, indicative of significant combustion activity in most kilns. Carbon monoxide (CO) exhibited elevated levels, average 5.5%, signifying incomplete combustion in several kilns. Nitrogen oxides (NO_x) averaged 1.7%, indicating that certain kilns attained sufficiently enough temperatures to initiate NO_x generation. Nitric oxide (NO), however, averaged 0.02% of the total emission concentrations.

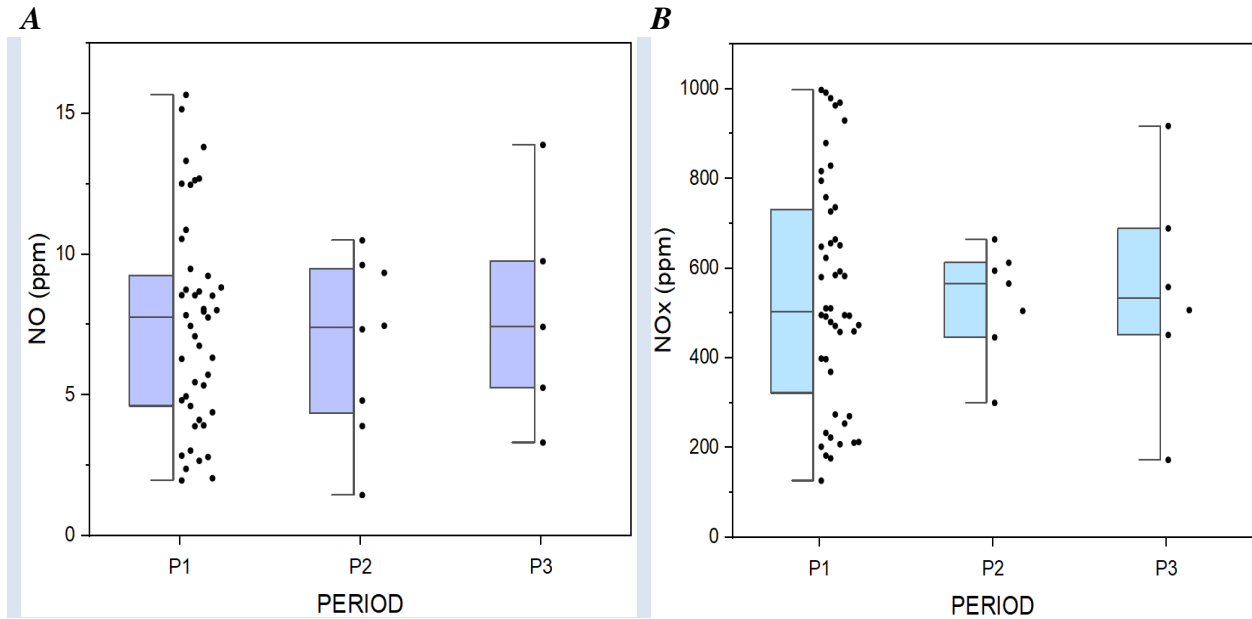


Figure 4.13: (A) - NO distribution over the different burning phases; (B) - NO_x distribution over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Primary Data)

The corresponding distributions and evolutions of NO and NO_x over time were low as shown in Figure 4.13 and Figure 4.14. The low NO and NO_x concentrations may be attributed to biomass fuels often used in these traditional kilns which generally exhibit lower nitrogen concentration than fossil fuels like coal. It can be noted from Figure 4.14 that there was a steep increase in NO and NO_x emissions for the first 8 hours and further increase in the emissions was gentle as the burning cycle continued.

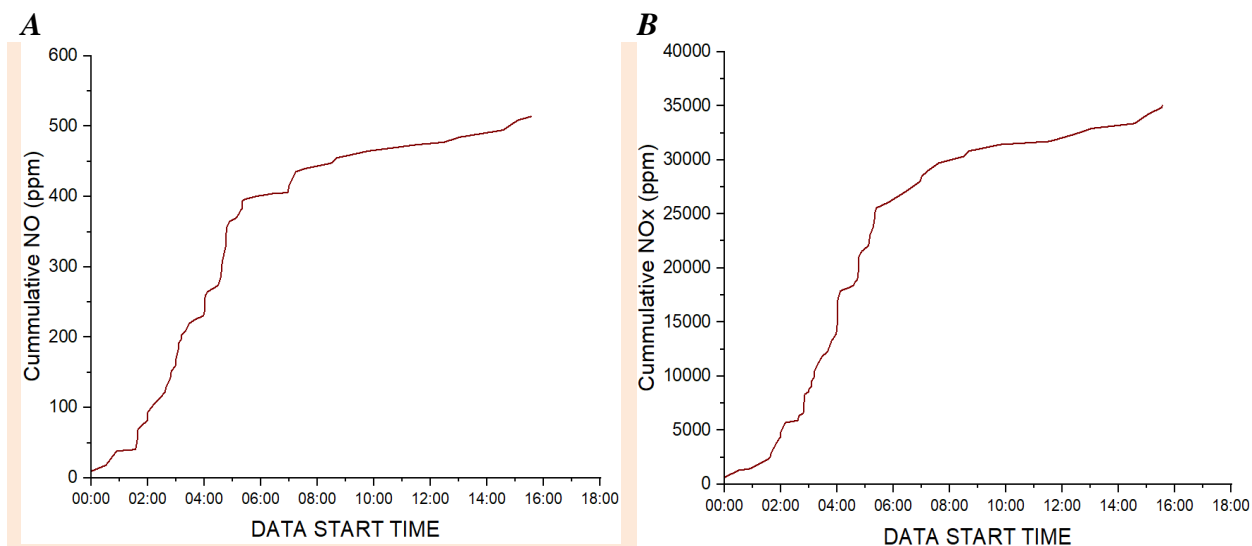


Figure 4.14: (A) - Cumulative NO; (B) - Cumulative NO_x emissions (Source; Primary Data)

4.3.1.1 Carbon Dioxide (CO₂)

CO₂ was the predominant emission with concentrations consistently exceeding those of other gases in the studied kilns. This verifies that a significant fraction of the carbon in biomass is fully oxidized to CO₂. Descriptive statistics revealed that CO₂ concentrations varied between 4,715.63 – 91,785.71 ppm, with a mean of $30,913.5 \pm 19,373.41$ ppm. The histogram of CO₂ was slightly right-skewed as shown in *Figure 4.15*. The histogram indicates that the majority of kilns emitted carbon dioxide ranging between 20,000 to 30,000 ppm, with emissions of approximately 30,000 ppm being the most common, representing approximately 22 kilns.

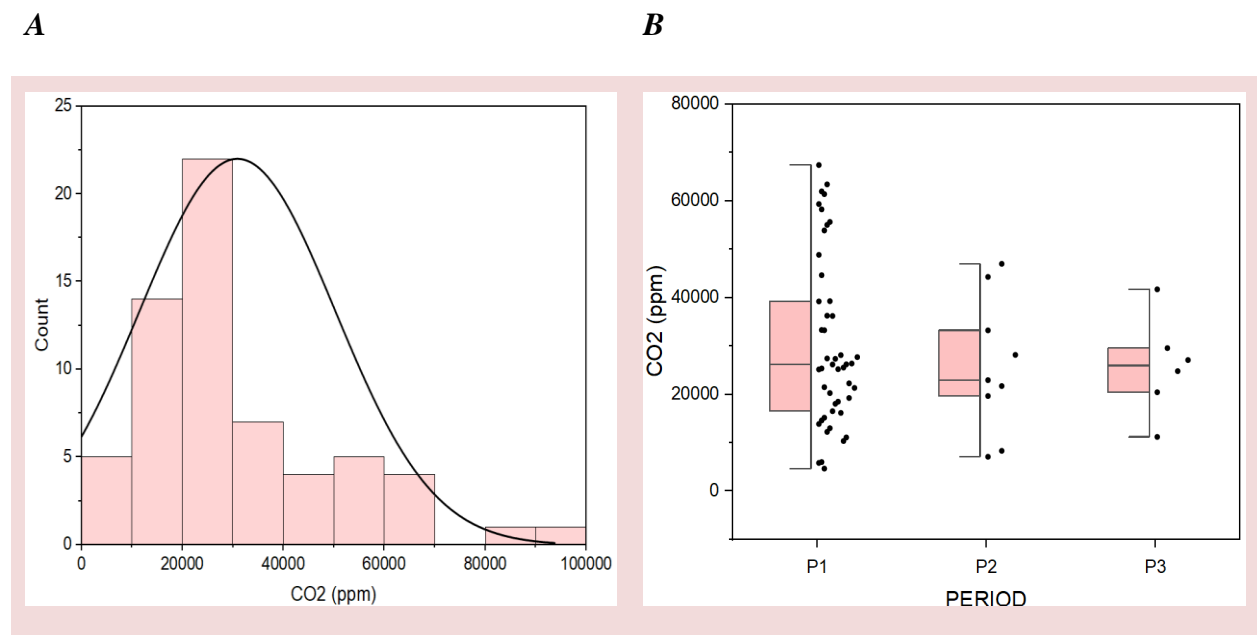


Figure 4.15: (A) - Distribution of CO₂ Emissions in Monitored Kiln; (B) - CO₂ distribution over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Author)

This study went ahead to analyze the CO₂ emissions in three 8-hour burning periods. The examination of CO₂ emissions, as illustrated in the box plot (*Figure 4.15*), demonstrates clear patterns throughout the kiln burning cycle. *Figure 4.16* shows their evolution in the entire cycle.

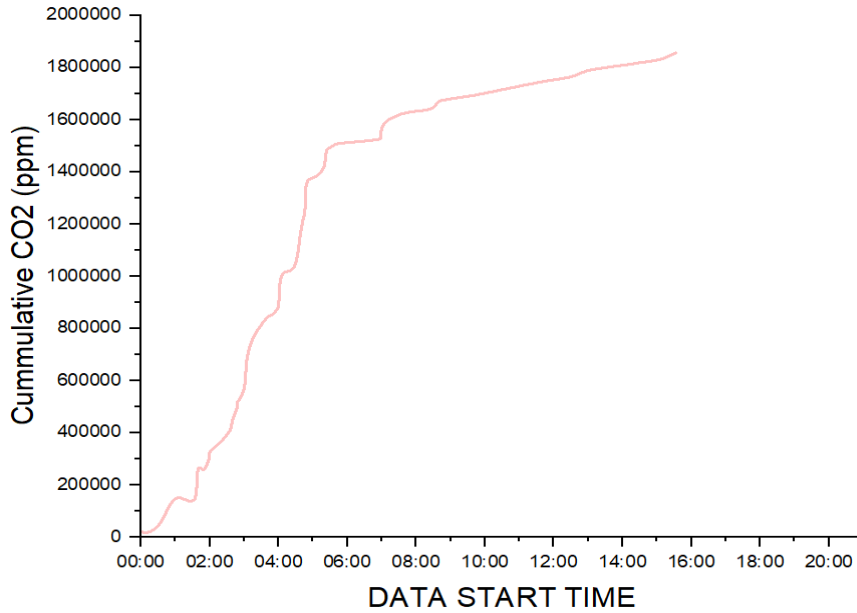


Figure 4.16: Cumulative CO₂ emissions evolution over time (Source; Primary Data)

In Period 1, the median CO₂ concentration was approximately 25,000 ppm, with an IQR spanning roughly 15,000 - 40,000 ppm. During Period 2, the median CO₂ emissions lowers and declined to around 22,000 ppm, and the IQR narrowed. During Period 3, the median CO₂ emissions rises to around 25,000 ppm, akin to P1, however with a more restricted IQR of 20,000 - 30,000 ppm. It can be noted from *Figure 4.16* that there was a steep increase in the evolution of CO₂ emissions for the first 8 hours and then they start to flatten out as the cycle continues.

4.3.1.2 Carbon Monoxide (CO)

CO emissions, albeit significantly lower than CO₂, exhibited substantial diversity among kilns, ranging from under 1,000 ppm to almost 4,000 ppm. This pattern indicates incomplete combustion resulting from inadequate oxygen delivery, elevated fuel moisture, or inappropriate kiln airflow. Descriptive statistics revealed that CO concentrations varied from 273.08 – 3,898.84 ppm, with a mean of $1,821.859 \pm 951.6619$ ppm. The histogram of CO below (*Figure 4.17*) was approximately normally distributed. The histogram indicates multiple peaks, with the highest frequencies occurring around 500 ppm, 1,000 ppm, and 2,000 ppm, each representing approximately 10 - 14 kilns. Very high CO levels above 3,500 ppm were rare and observed in only a few kilns.

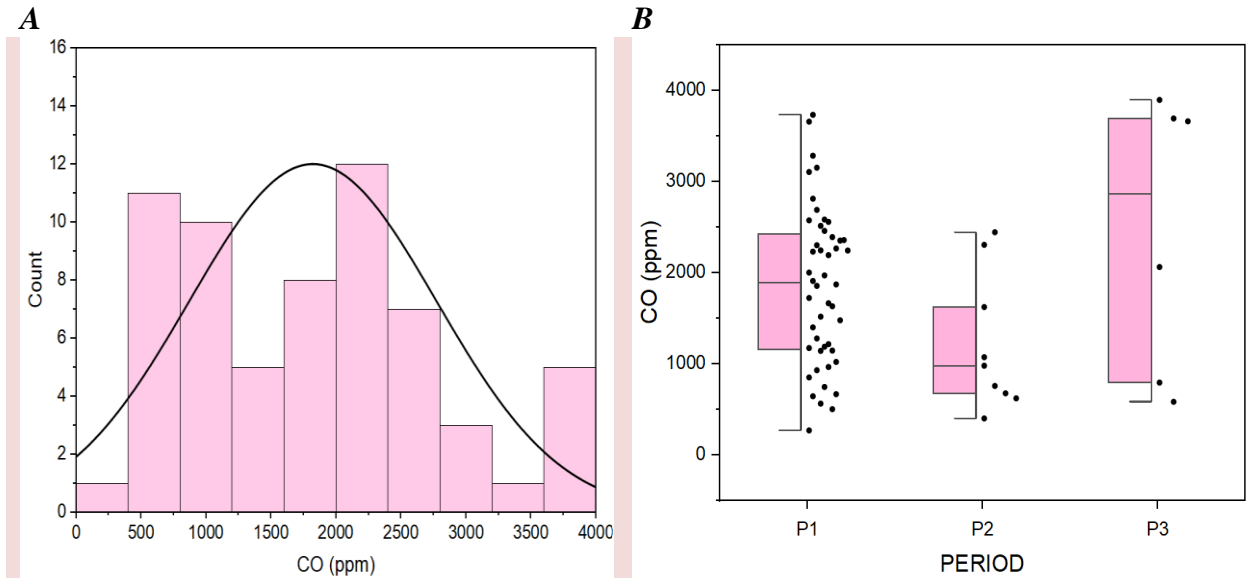


Figure 4.17: (A) - Distribution of CO Emissions in Monitored Kilns; (B) - CO distribution over the different burning phases; P1:0-8hours, P2:8-16hours, P3:16-24hours. (Source; Primary Data)

The box plot (Figure 4.17) above depicts the distribution of CO emissions during three periods while (Figure 4.18) below shows their evolution over time.

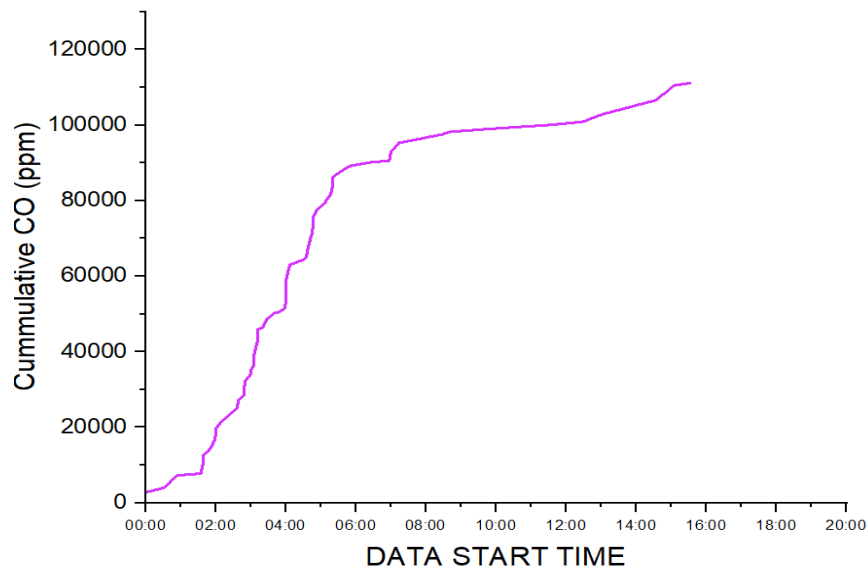


Figure 4.18: Cumulative CO emissions evolution over time (Source; Primary Data)

During Period 1, the median concentration was around 1,800 - 2,000 ppm, accompanied by a somewhat broad IQR of approximately 1,200 - 2,300 ppm. This fluctuation is likely due to disparities in biomass fuel moisture content, kiln sealing efficacy, and inconsistent combustion

during the ignition phase. Period 2 demonstrated a significant decrease in CO emissions, with a median of around 900 ppm and a more restricted IQR of 500 - 1,500 ppm. A reduced number of outliers signifies more uniformity among kilns. This phase is characterized by more stable combustion conditions wherein persistent high temperatures promote the oxidation of carbon monoxide to carbon dioxide. Finally, Period 3 had the highest median CO concentration at about 2,800 ppm and the broadest IQR of 600 - 3,600 ppm. Numerous severe outliers were seen, indicating substantial kiln-to-kiln variability. It can be noted from *Figure 4.18* that there was a steep increase in the evolution of CO emissions for the first 8 hours and then they start to flatten out as the cycle continues.

4.3.2 Emission factors

The carbon mass balance approach was employed to calculate the emission factors of the pollutants in this study. The primary assumption for this approach was that all carbon content in the fuel was released as carbonaceous gases, specifically CO₂ and CO. The emission factors of CO and CO₂ were expressed as grams of pollutant per kilogram of wood fuel burned (g/kg). The computation of emission factors from the 63 kilns revealed notable variability in both carbon monoxide (CO) and carbon dioxide (CO₂) emissions per kilogram of fuel consumed. The mean emission factor for CO was 18.81 ± 9.84 g/kg, with values ranging from 3 g/kg to 40 g/kg. For CO₂, the mean emission factor was 500.82 ± 313.85 g/kg, with a range of 76 g/kg to 1,487 g/kg.

4.4 Influence of the Characteristic of Biomass on Emissions from Traditional Brick Kilns

For the third objective, the study sought to understand how the characteristics of biomass influenced the emissions during the brick production process. Having established the biomass characteristics, that is moisture content, calorific value and fuel quantity, and the emissions associated with traditional brick kilns, this study further examined whether there was a relationship between these characteristics and the emission levels.

4.4.1 Influence of Moisture Content On Emissions in Brick Kilns

This aimed to understand if the moisture of fuel used in kilns had an impact on the emissions released into the atmosphere. There was a positive association between moisture content and CO emissions (*Figure 4.19*). The fitted line shows that an increase in moisture content correlates with an increase in CO emissions.

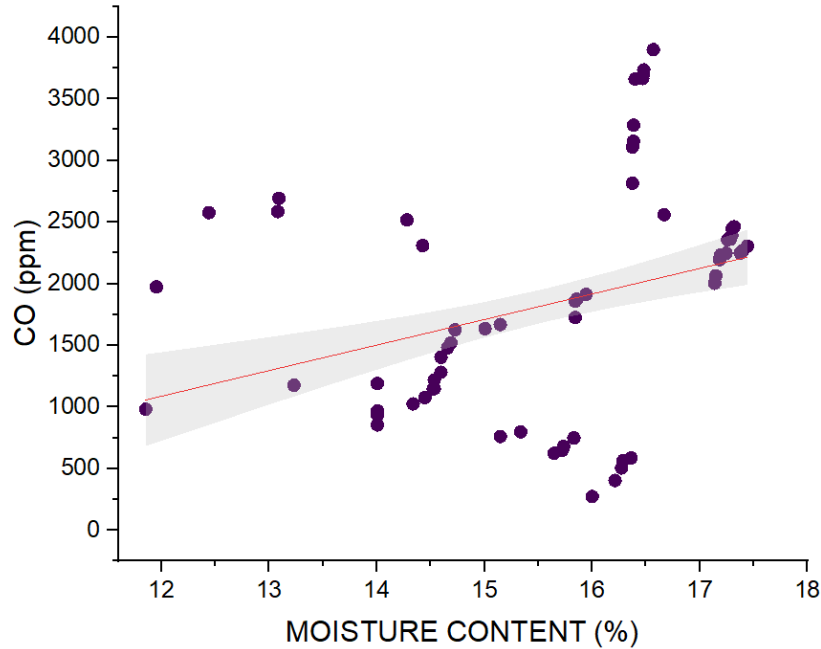


Figure 4.19: Relationship between Moisture Content and CO (Source; Primary Data)

There was a positive and statistically significant relationship between moisture content of hardwood fuel and CO emissions. The output (Table 4.4) demonstrated statistical significance, $F(1,61) = 6.56$, $p = 0.013$, with a $R^2 = 0.1$, signifying that 10% of the variance in CO emissions is accounted for by moisture content.

Table 4.4: Regression Output for Moisture Content and Emissions (Source; Author)

Moisture Content	Carbon Monoxide (CO)	Carbon Dioxide (CO ₂)
Coefficient	207.3017	1614.307
Constant	-1400.146	5822.987
P-Value	0.013	0.352
R ²	0.0971	0.0142

The regression coefficient was $\beta = 207.3$, $p < 0.05$, indicating that for each 1% rise in moisture content, CO emissions escalated by almost 207.3 ppm. The linear regression model is:

$$CO(ppm) = -1400.15 + 207.3017 \times \text{Moisture Content (\%)} \quad (4.3)$$

On the other hand, the relationship between moisture content and CO₂ implies that the moisture content does not significantly affect the levels of CO₂. The output (Table 4.4) lacked statistical significance at the 5% significance level, $F(1,61) = 0.88$, $p = 0.352$, $R^2 = 0.014$. The regression

coefficient was $\beta = 1614.31$; however, there is insufficient evidence of a correlation between moisture content and CO₂ emissions.

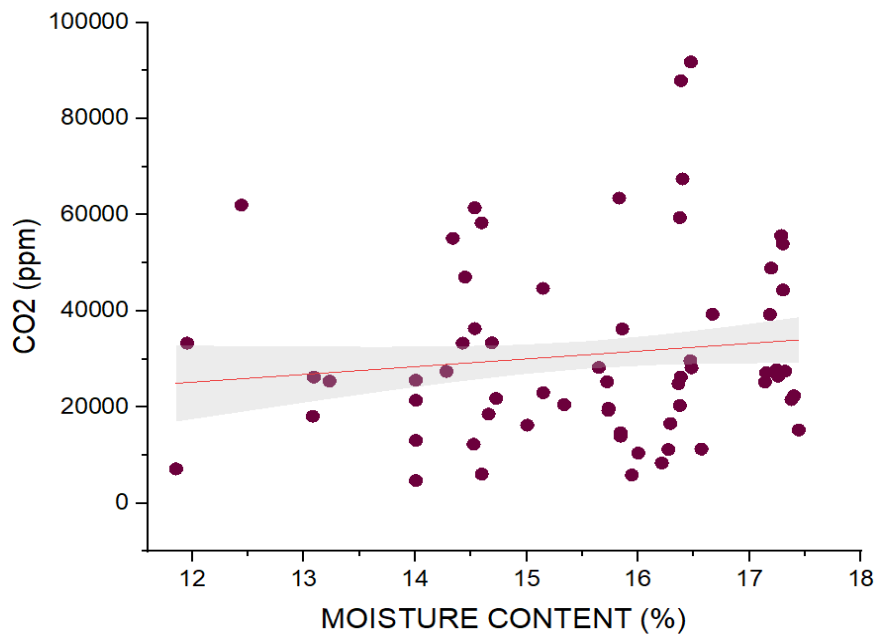


Figure 4.20: Relationship between Moisture Content and CO₂ (Source; Primary Data)

There was a weak association between moisture content and CO₂ emissions (*Figure 4.20*); still, the data points are widely scattered, and the slope of the regression line is minimal. This corresponds with the regression findings, which lacked statistical significance at the 5% threshold.

4.4.2 Influence of Calorific Value On Emissions in Brick Kilns

This aimed to understand if the calorific value of fuel used in kilns had an impact on the emissions released into the atmosphere. There was a negative correlation between calorific value and carbon monoxide emissions (*Figure 4.21*). As calorific value rises, CO emissions diminish, signifying that fuels with more energy content combust more thoroughly and cleanly.

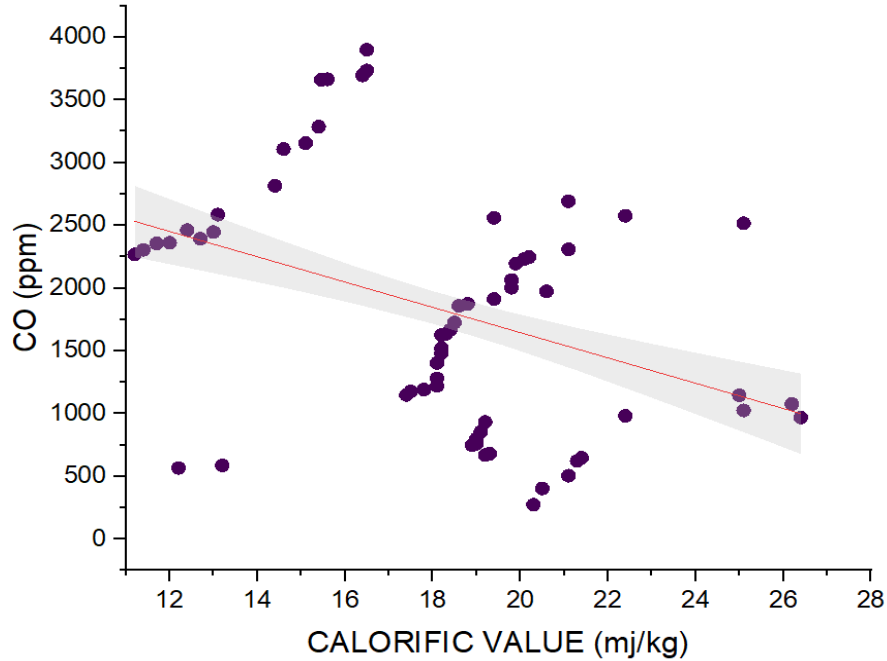


Figure 4.21: Relationship between Calorific Value and CO (Source; Primary Data)

A linear regression analysis was performed to evaluate the impact of biomass calorific value (MJ/kg) on CO emissions.

Table 4.5: Regression Output for Calorific Value and Emissions (Source; Author)

Calorific Value	Carbon Monoxide (CO)	Carbon Dioxide (CO ₂)
Coefficient	-100.72	-1396.29
Constant	3659.76	56391.59
P-Value	0.002	0.038
R ²	0.1483	0.0688

The output (Table 4.5) for carbon monoxide emissions was statistically significant, $F(1,61) = 10.62$, $p = 0.002$, with a R^2 of 0.15. This signifies that 15% of the variation in CO emissions is accounted for by calorific value. The linear regression model is:

$$CO(ppm) = 3659.76 - 100.72 \times \text{CalorificValue (MJ/Kg)} \quad (4.4)$$

There was a negative association between CO₂ emissions and increasing calorific value (Figure 4.22). Nevertheless, the dispersion of the data points is broader, and the gradient is less pronounced.

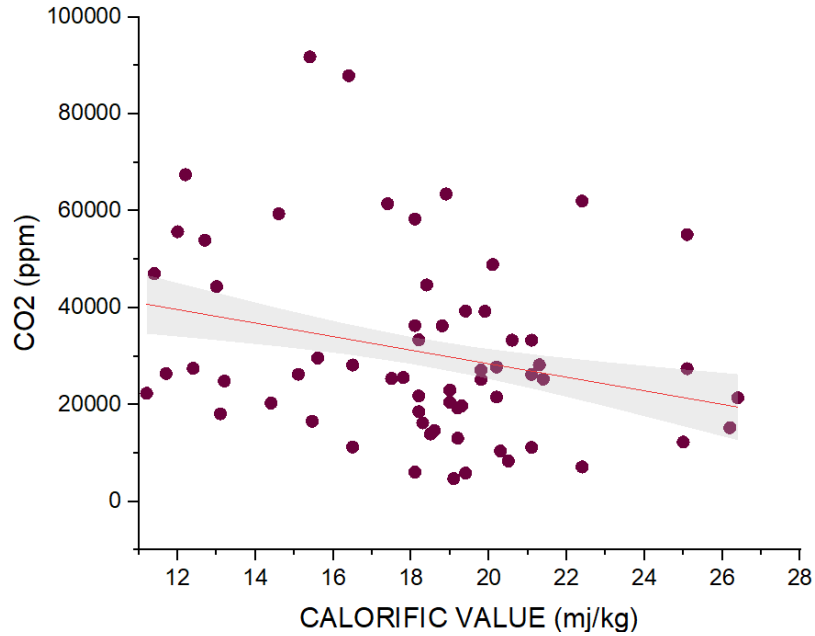


Figure 4.22: Relationship between Calorific Value and CO₂ (Source; Primary Data)

The regression output (*Table 4.5*) for CO₂ was statistically significant at the 5% level ($p = 0.038$), however it had a lower R² of 0.07. This indicates a diminished correlation, with increased calorific values linked to decreased CO₂ emissions. The linear regression model is:

$$CO_2(ppm) = 56391.59 - 1396.29 \times \text{Calorific Value (MJ/Kg)} \quad (4.5)$$

4.4.3 Influence of fuel amount on emissions

This aimed to understand if the amount of fuel used in kilns had an impact on the emissions released into the atmosphere.

4.4.3.1 Carbon Monoxide

The scatter plot (*Figure 4.23*) shows a negative association between quantity of fuel used and CO emissions meaning the greater the fuel amount used, the less the CO emissions.

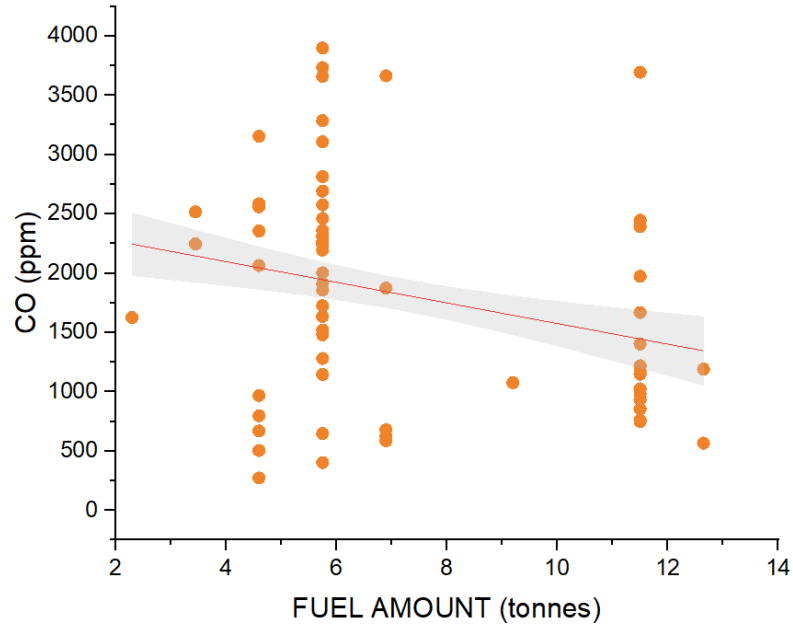


Figure 4.23: Relationship between Fuel amount and CO (Source; Primary Data)

A linear regression analysis was conducted to ascertain if the quantity of fuel predicted carbon monoxide emissions.

Table 4.6: Regression Output for Fuel Amount and Emissions (Source; Author)

Fuel Amount	Carbon Monoxide (CO)	Carbon Dioxide (CO ₂)
Coefficient	-86.90	1211.34
Constant	2445.25	22223.59
P-Value	0.037	0.156
R ²	0.07	0.033

The output (Table 4.6) demonstrated statistical significance, $F(1, 61) = 4.56$, $p = 0.037$, with fuel quantity accounting for roughly 7% of the variation in CO emissions ($R^2 = 0.07$). The quantity of fuel was a negative predictor of carbon monoxide emissions and the linear regression model is:

$$CO(ppm) = 2445.25 - 86.9 \times \text{Fuel Amount (t)} \quad (4.6)$$

4.4.3.2 Carbon dioxide

There is a slightly positive association between CO₂ emissions and increasing fuel quantity as shown in the scatter plot (Figure 4.24). The figure shows that as more fuel was used in the kilns, the temperatures in the kilns increased leading to more complete combustion of the carbon resulting into more carbon dioxide levels being emitted.

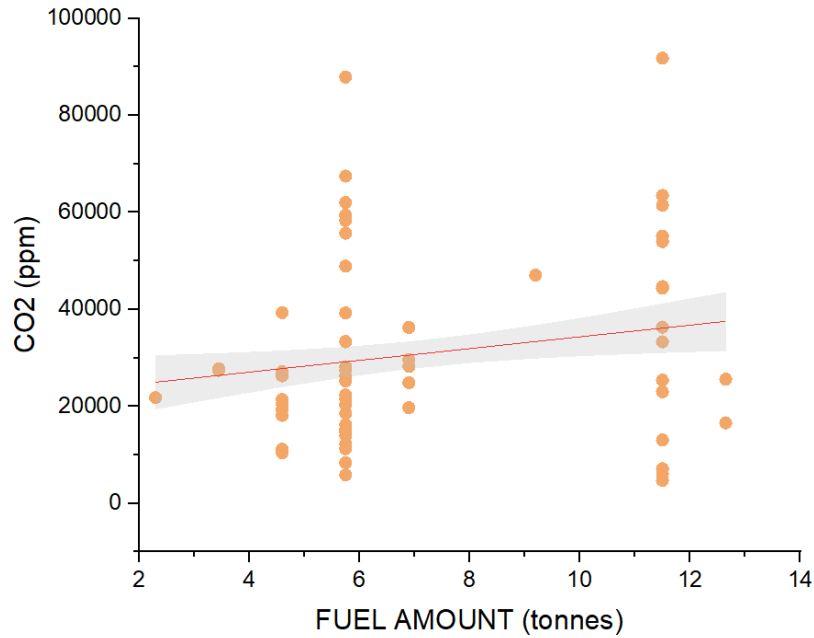


Figure 4.24: Relationship between Fuel amount and CO₂ (Source; Primary Data)

A simple linear regression was performed to assess the predictive relationship between fuel quantity and CO₂ emissions. The output (*Table 4.6*) lacked statistical significance, $F(1, 61) = 2.06$, $p = 0.156$, suggesting that fuel quantity was not a dependable predictor of CO₂ emissions. The coefficient of determination indicated that fuel quantity accounted for just 3.3% of the variation in CO₂ emissions ($R^2 = 0.033$). However, it indicated a tendency for CO₂ levels to rise with increased fuel quantities, lacking statistical validation.

CHAPTER FIVE: DISCUSSION

5.1 Introduction

This chapter focuses on discussing the results in line with the objectives that guided the study. This is through the discussion of findings with reference to existing literature as per the objectives of the study.

5.2 Characteristics of Biomass used in Traditional Brick Kilns

For the first objective, the study aimed to determine the different characteristics of biomass used in the traditional brick kilns by type, physical properties and chemical properties. These were obtained from the observation checklists and in-situ measurements.

5.2.1 Biomass types

Literature indicates that there are three major types of biomass used as fuel that is hardwood, softwood and agricultural residues (Hashemi & Cruickshank, 2015; Hood et al., 2013). The research findings, however, indicate that there was only one type of biomass used as fuel for these 63 traditional kilns studied, that is, hardwood. The hardwood used was in a variety of species (*Figure 4.1*) which were utilized either individually or in combinations depending on the availability and affordability. The study discovered a variety of biomass species used as fuel in traditional brick kilns, with usage patterns differing between single or dominant use and mixed utilization with other species. The selection of biomass species seems to be determined by factors including availability, combustion properties, and cultural familiarity. Two species emerged as the primary or exclusive fuels that is eucalyptus and mugavu. Eucalyptus, locally referred to as Kalitunsi, served as the only or principal fuel in thirty-six (36) kilns. The preference is likely attributable to its high calorific value, ranging from 18.5 – 21.4 (MJ/Kg), as shown in this study. Mugavu (*albizia coriaria*) is utilized exclusively or predominantly in twenty-three (23) kilns and is preferred for its slow combustion characteristics, elevated heat production, and prolonged ember duration, which facilitate sustained high temperatures during brick burning (Katende et al., 2000). Nonetheless, it is less prevalent than eucalyptus, potentially restricting its exclusive application to regions with its availability. The exclusive use of these species signifies dependence on their reliable combustion characteristics, perhaps diminishing the necessity for frequent fuel input throughout the fire process.

The other species were mostly utilized in conjunction with others, indicating a strategy to optimize fuel supply and performance. Mango (*Mangifera indica*), locally known as muyembe, was employed in twenty-three (23) kilns in a blended pattern. It is frequently utilized in conjunction with hardwoods to facilitate rapid ignition and temperature escalation. Jackfruit (*Artocarpus heterophyllus*), locally known as fene, was utilized in seventeen (17) kilns and its wood is thick but very resinous, generating moderate heat (Jenkins et al., 1998). Avocado (*Persea americana*) was used in ten (10) kilns, avocado wood is comparatively softer and more accessible from trimmed trees inside agroforestry systems. It was noted to combust rather swiftly, therefore its varied application to enhance the combustion of longer burning hardwoods. Muvule (*Milicia excelsa*) was found in only eight (8) kilns and in a mixed condition, perhaps owing to its rarity. Mutuba (*Ficus natalensis*) was utilized in just three (3) kilns while Musizi (*Maesopsis eminii*) was used in two (2) kilns as these species possess lower calorific values, averaging 14.7 MJ/Kg, and are often less preferred for brick burning. Their existence indicates opportunistic use in the absence of favored species. Usage patterns demonstrated that sole or primary use was designated for species that offer significant and stable burn rates, guaranteeing consistent combustion. Mixed usage is an alternative and an adjustment to resource availability, economic considerations, and the necessity to enhance fire dynamics through the integration of fast and slow burning fuels.

The use of hardwood as fuel is mainly attributed to its longer combustion efficiency and proven performance in comparison to softwood and/or agricultural residues. In support of the aforementioned finding, it was revealed that softwood burns quickly and may not heat up long enough to fully burn bricks (Amaral et al., 2014). It also produces excessive smoke and is unfamiliar to rural brick makers or not locally marketed in suitable quantities. A similar study in India observed the same findings, highlighting that brick manufacturers use hardwoods for their reliable heat production (Kumar et al., 2015). However, extended utilization of hardwood leads to deforestation (FAO and UNEP, 2021).

In conclusion, the dependence on hardwoods is in line with existing literature about energy efficiency, although it raises issues about sustainability and forest damage. The utilization of other biomass types such as agricultural residues is limited/ non-existent in traditional kilns, highlighting a need in sustainable fuel transitions within the Ugandan brick sector.

5.2.2 Moisture content

The physical property of biomass ascertained for this study was moisture content due to its impact on the combustion of biomass. This was obtained for samples of hardwood used in all 63 kilns using a moisture meter and the results were ranging between 11.86 -17.44%. Descriptive analysis indicated that the mean moisture content is $15.5 \pm 1.43\%$. The findings indicated that reduced moisture content was often linked to hardwood species including mugavu, mvule and eucalyptus, especially when the wood had been kept for prolonged durations prior to utilization. In contrast, elevated moisture levels were often associated with mixed species loads that included fruit woods like as mango, jackfruit and musizi, which often have greater natural water content (Jenkins et al., 1998).

Differences in moisture levels across different kilns indicate a substantial impact of fuel composition and fuel management strategies. For example, a kiln which utilized a combination of mugavu, avocado and eucalyptus, exhibited a comparatively low moisture content of 13.12%, probably attributable to the utilization of hardwoods with less moisture content. However, a kiln that used 100% eucalyptus had the greatest moisture content (17.44%), potentially attributed to recent harvesting before combustion, as newly cut eucalyptus can possess significant moisture content despite its comparatively thick structure.

Another factor influencing moisture content levels could be the post-harvest storage conditions by kiln operators. Kilns that stored wood reducing direct exposure to rain typically maintained moisture levels. This tendency corresponds with the findings from previous studies which indicated that covered storage can reduce moisture content by as much as 5% relative to open air ground storage (Jetter et al., 2009). In contrast, several elevated moisture levels were associated with fuels that were kept in open yards.

The existing environmental conditions during sampling also could have influenced the observed variation in moisture content. The data recorded during rainy times of the season exhibited a greater moisture content (by roughly 2–3%) compared to those recorded during drier periods. This seasonal phenomenon reflects the findings which demonstrated that elevated relative humidity might affect drying processes and increase moisture content in biomass fuels (Zhang & Smith, 2007). In addition, fuel diameter and sizes affected drying efficiency. Thicker logs and un-split

pieces, prevalent in various kilns dried at a slower rate than smaller or split logs, hence preserving greater moisture (Jenkins et al., 1998).

During burning operations, elevated moisture content enhances the latent heat necessary for water evaporation during combustion, resulting in reduced kiln temperatures and leading to incomplete combustion along with increased emissions (Demirbas, 2004). Therefore, regulating fuel moisture content by species selection, optimized storage, and pre-combustion preparation is crucial for improving combustion efficiency and minimizing emissions. In addition, FAO (2010) stressed that pre-drying biomass markedly enhances combustion quality and emission characteristics. In conclusion, the difference in moisture content shows irregularities in preparation of fuel used. Ensuring fuel drying may reduce pollution levels and improve combustion efficiency, as evidenced by previous studies.

The study further analyzed the moisture content over the entire burning cycle (*Figure 4.4*). This involved splitting the entire burning cycle into three burning periods that is Period 1 which is 0 – 8th hour, Period 2 which is 8th -16th hour and Period 3 which is 16th – 24th hour as shown in previous studies (Weyant et al., 2016). This was done to understand the change in moisture content in the biomass during the burning process. In the first period, the median moisture level was about 15.8%, with a broad interquartile range (IQR) and clear outliers at both ends (11.8% and 17.5%). This showed that the process was quite variable which could be attributed to the use of different species combinations with varying moisture content. In Period 2, the median went down a little to about 15.6%, and the IQR was narrower. This means that control was better, probably due to increased combustion temperature, but not perfect. The median moisture content went further down to around 14.2% by Period 3. This could be attributed to more regulated combustion but the IQR was broader than Period 2 probably attributed to feeding of fuel in the final cooling period when burning is coming to an end. This shows that ensuring homogeneity in fuel used and procedures is essential for the production of quality bricks. This is supported by the fact that Period 3 has less fluctuation and more regulated moisture levels. Previous studies indicate that too much moisture can hurt thermal properties or compressive strength of the final product, which shows how important it is to regulate moisture, not just for making bricks, but also for their performance (Barreira et al., 2019; Bompa & Elghazouli, 2020).

In conclusion, the findings indicate that further combustion facilitated a transition from significant fluctuation in Period 1 to more stability in the moisture content in Period 3. This change is in line with the larger objective of the brick industry to get stable moisture levels to improve the quality of the bricks and the efficiency of manufacturing.

5.2.3 Calorific Value

The calorific value (MJ/Kg) of all 63 samples was obtained and ranged between 11.2 -26.4MJ/Kg. Comparable ranges have been documented in biomass research, with tropical hardwoods generally displaying elevated calorific values 18–20 MJ/kg (Demirbas, 2004; Grover & Mishra, 1996). The calorific value is essential for optimal combustion and energy efficiency (Bhattacharya et al., 2002). Descriptive analysis indicated that the mean calorific value is 18.25 ± 3.64 MJ/Kg.

Various wood species possess essentially distinct calorific values owing to differences in lignin, cellulose, and extractive content (Sheng & Azevedo, 2005). Hardwoods like muvule and mugavu often possess elevated lignin levels, resulting in increased calorific value (CV), while others like mango, have somewhat lower CV. The average calorific value (CV) obtained in this study is 18.25 MJ/kg, which is within the 16–19 MJ/kg range reported for biomass fuels in prior studies (Mugo & Ong, 2006; Okot, 2019). Global studies indicate that responsibly harvested, adequately dried tropical hardwoods often produce CV values above 18 MJ/kg (Khan et al., 2009). In this study, around 65% of the kilns that were examined (41 out of 63) met or exceeded this level. This suggests that there is a lot of utilization of biomass that is dry enough. Because of this, these kilns are more likely to burn fuel more completely, which means less pollution. On the other hand, the other 35% of kilns utilized fuels with calorific values lower than 18 MJ/kg, which might mean they were using biomass that wasn't dried adequately. This conclusion is similar to a study that found low-CV fuels tend to generate more unburned carbon and gaseous pollutants since they don't burn well (Saidur et al., 2011). In summary, the calorific values indicate satisfactory energy content in the biomass utilized as fuel for traditional kilns.

Similarly, the calorific value of biomass fuels was analyzed along the entire 24-hour cycle (*Figure 4.6*) in three 8-hour periods. In the first period, the median calorific value was roughly 18 MJ/kg with a broad IQR, although it could be anywhere from 11 MJ/kg to 26 MJ/kg. This wide range of values shows that different species of hardwood fuels are being used whether hardwoods with lower quality or those that haven't been dried well enough. The existence of fuels below 18 MJ/kg

suggests that certain kilns used energy sources that weren't the best due to their availability. The median calorific value rose slightly to around 19 MJ/kg in the second period, while the interquartile range, approximately 15 - 20 MJ/kg, became substantially smaller. During this time, almost all fuels went beyond 18 MJ/kg, which means they burned more efficiently and produced less pollution. Period 2 shows a considerable improvement in energy quality and consistency compared to Period 1. On the other hand, the third period saw a drop, with the median CV dropping to about 16.5 MJ/kg and most values falling between 12.5 and 20 MJ/kg. This reduction means that the biomass energy content is getting depleted towards the end of the burning process. The variability in P1 is similar to studies showing that informal brick kilns commonly use mixed biomass hardwood species, which makes the kiln work less well and makes the fire conditions less stable (Bhattacharya et al., 2002).

In conclusion, Period 2 is the best time since most fuels exceed the 18 MJ/kg standard and have stable energy quality indicating peak combustion. Period 1 had some high-CV fuels, but it also had a lot of variation, which might hurt efficiency. Period 3, on the other hand, shows depletion of the energy content in the fuel, which might mean that the burning isn't as efficient. These results show how important it is to make sure that kiln operators always have access to well-dried hardwoods or other high-energy biomass in addition to understanding the combustion properties of the wood used. This will improve kiln efficiency and lower emissions.

5.2.4 Fuel Quantity

The allocation of fuel quantities (in tonnes) utilized among the 63 traditional brick kilns was also analyzed which ranged from 2.3 – 12.65 tonnes. Descriptive analysis indicated that the mean fuel amount was 7.17 ± 2.89 tonnes. The histogram (*Figure 4.7*) indicated that the majority of kiln firings utilized between 4 and 6 tonnes of fuel, based on the number of bricks being burnt. Less kilns indicated fuel use at the extremes, with some utilizing as little as 2-3 tonnes and others necessitating as much as 10-12 tonnes, while a few exceptional instances documented up to 14 tonnes. This is similar to a study where kilns ranging from 7,000 to 20,000 bricks were utilizing average wood fuel of about 6.7 tonnes (Olweny et al., 2017). Furthermore, for the total of approximately 1.15 million bricks burnt in the 63 kilns studies, the amount of biomass wood fuel required to fire 1000 bricks was found to be 330kg. This is in line with previous studies in Sudan where it was reported to be 70.2 – 960kg (Alam, 2006).

The study further analyzed the fuel quantities used throughout the three firing periods (*Figure 4.8*). During Periods 1 and 2, median consumption fluctuated between 6 and 8 tonnes, nevertheless, the interquartile ranges were extensive, and several outliers were identified. This signifies considerable differences in kiln procedures throughout the start times, with certain operators utilizing either more or less fuel than the average. Period 3 had a more restricted interquartile range, and a reduced number of extreme outliers. This indicates a transition towards enhanced consistency and a marginal decrease in fuel consumption during the latter firing cycle. The results demonstrated that biomass use in the tested traditional kilns varies significantly among operators, with total usage ranging from 2 to 14 tonnes, predominantly relying on 4 - 6 tonnes each cycle depending on the number of bricks to be burnt. This study further reveals that early firing times had significant changes in fuel use, but subsequent periods demonstrated more consistent and moderate usage patterns. This is mainly attributed to the fact that biomass is generally slower at ignition in comparison to other fuels such as coal and would therefore require more quantities at the start to aid combustion (Saidur et al., 2011). Therefore, the study concluded that the biomass used is affected by kiln dimensions and operator practices that further influence fuel supply in traditional kilns.

5.2.5 Impact of moisture content on calorific value

The study sought to assess the impact of biomass properties on emissions and the link between moisture and calorific value is a fundamental process. A negative association was noted between moisture content and calorific value (*Figure 4.9*), aligning with existing biomass combustion research. Biomass with higher moisture content needs additional energy to vaporize water during burning, thereby diminishing its net calorific value.

Regression analysis indicated a statistically significant negative correlation between biomass moisture content and calorific value, $F(1, 61) = 20.02, p < 0.0001$. The model accounted for around 24.7% of the variation in calorific value ($R^2 = 0.247$). The findings demonstrated that for each 1% rise in moisture content, the calorific value diminished by approximately 1.26 MJ/kg ($\beta = -1.26, p < 0.0001, 95\%$). The linear regression model (*equation 4.1*) was:

$$\text{Calorific Value (MJ/Kg)} = 37.90 - 1.26 \times \text{Moisture Content (\%)}$$

This data corroborates the documented adverse correlation between moisture content and biomass energy quality. The inverse correlation between calorific value and moisture content has been well-documented in biomass combustion literature. Studies show that moisture content diminishes the heating value of biomass by absorbing latent heat during vaporization, thereby diminishing the net calorific value of the fuel (Demirbas, 2004; Khan et al., 2009). McKendry (2002) also highlighted that biomass with elevated moisture content has less useable energy, requiring supplementary energy for water evaporation prior to effective burning. Another study states that a 1% rise in moisture content may reduce calorific value by as much as 0.2 MJ/kg, contingent upon the kind of biomass (Oberberger & Thek, 2004). The results of this investigation align with these observations, indicating that samples with moisture content over 20% exhibited markedly reduced calorific values. In summary, the findings support the results that moisture content diminishes calorific value, so indirectly fostering inefficient burning. This validates the dual influence of moisture on emission dynamics and energy efficiency. Prioritizing biomass drying is essential for good emission control and fuel optimization in traditional brick kilns.

5.2.6 Fuel quantity and moisture content in brick kilns.

Further analysis sought to assess the influence of fuel quantity on the moisture content of biomass used. A negative association was noted between fuel quantity used and moisture content of the fuel (*Figure 4.10*). This indicates that the more biomass fuel utilized, the less the moisture content since it is used to vaporize more water during burning. This tendency aligns with the regression findings, which revealed a statistically significant negative coefficient ($\beta = -0.16$, $p = 0.011$). the linear regression model (*equation 4.2*) was:

$$\text{Moisture Content}(\%) = 16.67 - 0.16 \times \text{Fuel amount (t)}$$

Despite the downward slope of the regression line, the dispersion of data points indicates a somewhat weak association. The moisture content values are predominantly concentrated between 13% and 17% across various fuel quantities, exhibiting significant fluctuation around the fitted line. This variation illustrates the impact of additional parameters, like wood species, drying techniques, and ambient conditions, which were not explicitly regulated in this model. The fitted regression line indicates that for every extra ton of fuel consumed, the average moisture content diminishes by around 0.16%. However, the R^2 value (0.1013) highlights that the quantity of fuel accounts for just a little fraction of the overall change in moisture content. The scatter plot

indicated that greater biomass use correlates with a marginal decrease in moisture content but the association is weak. This is because decrease in moisture content is also highly reliable on other factors like combustion temperatures that evaporate the water content in the wood. This is supported by studies that have indicated that high biomass fuel moisture content can slow down the combustion speed, increase the burning time which further increases the quantity of biomass required to achieve adequate combustion temperatures (Zhao et al., 2021). The results, therefore, indicate that greater quantities of wet biomass would be required in order to achieve the required combustion temperatures in kilns. This will help inform construction professionals, brick makers and operators on the importance of proper storage and drying of wood before use as fuel in kilns so as to reduce on the quantities required in kilns.

5.2.7 Fuel quantity and calorific value in brick kilns.

The scatter plot (*Figure 4.11*) indicated no major relationship between fuel quantity of biomass and calorific value. A linear regression analysis was performed to investigate the correlation between fuel quantity (in tonnes) and the calorific value of the biomass. The model lacked statistical significance, $F(1, 61) = 0.14$, $p = 0.708$. The coefficient of determination ($R^2 = 0.0023$) indicated that the fuel amount accounted for less than 1% of the variance in calorific value. This is mainly because the biomass utilized was of different species with varying calorific values influencing the combustion process.

Generally, the results above showed that a large number of kilns still rely on substandard biomass, which might hurt both energy efficiency and emissions performance. Kilns utilizing biomass in the 12–14 MJ/kg range may exhibit reduced efficiency and an increased carbon footprint per brick manufactured (Smith et al., 2014). In conclusion, reduced calorific value biomass results in incomplete combustion and elevated emissions, necessitating the burning of more fuel to get equivalent thermal output. Therefore, brick makers and operators should ensure to purchase fuel and species with high calorific value like eucalyptus so as to ensure more efficient combustion in brick kilns.

5.3 Emissions from Biomass Fueled Brick Kilns

5.3.1 Gaseous Emissions

For the second objective, the study aimed to determine the emissions associated with the biomass used in traditional brick kilns. This section provided the findings on the different emissions

associated with the biomass fuel in the traditional brick kilns. These were obtained from in-situ measurements. The major emissions obtained from the field data include; carbon monoxide (CO), carbon dioxide (CO₂), Nitric Oxide (NO), Nitrogen oxides (NO_x) (*Figure 4.12*). Carbon dioxide (CO₂) exhibited the greatest concentrations among the studied emissions, averaging 92.8%, indicative of significant combustion activity in most kilns. Carbon monoxide (CO) exhibited elevated levels, average 5.5%, signifying incomplete combustion in several kilns. Although the levels of CO₂ differ across kilns, it was confirmed as having the highest-level emission values in other studies (Asif et al., 2021; Bhat et al., 2014). Nitrogen oxides (NO_x) averaged 1.7%, indicating that certain kilns attained sufficiently enough temperatures to initiate NO_x generation. Nitric oxide (NO), however, averaged 0.02% of the total emission concentrations.

The low NO and NO_x concentrations (*Figure 4.14*) may be attributed to biomass fuels often used in these traditional kilns which generally exhibit lower nitrogen concentration than fossil fuels like coal. Their corresponding distributions and evolutions over time were low. The creation of NO and NO_x during combustion is significantly influenced by the nitrogen concentration of the fuel; hence, the low nitrogen present in biomass intrinsically, typically 0.03 – 0.1% by dry weight, constrains the production of nitric oxide (Cowling & Merrill, 1966). Secondly, the combustion conditions in traditional kilns are defined by low and fluctuating temperatures and oxygen-restricted surroundings. In contrast to industrial furnaces that may reach flame temperatures over 1300°C. These findings align with prior research indicating comparatively low NO_x and NO emissions from biomass burning in contrast to fossil fuels (Tissari et al., 2008). Tissari et al. (2008) also noted that in small-scale wood combustion, the generation of NO_x was negligible, but CO and organic carbon emissions were predominant. Previous studies observed that emissions from simulated clamp kilns predominantly consisted of CO and CO₂, whereas NO_x constituted a negligible portion (Akinshipe & Kornelius, 2018).

The emphasis of this study was therefore placed on quantifying the amounts of CO and CO₂, since these represent the principal gaseous emissions associated with biomass combustion in traditional brick kilns (Chung & Seinfeld, 2002). These gases significantly contribute to air pollution and climate change, with CO resulting from incomplete combustion and CO₂ being the primary greenhouse gas released during biomass burning (Asif et al., 2021). There is need of quantifying CO and CO₂ emissions from traditional brick kilns to evaluate environmental and health effects.

5.3.1.1 Carbon Dioxide (CO₂)

CO₂ was the predominant emission with concentrations consistently exceeding those of other gases in the studied kilns, with the majority of values concentrated in the 50,000–100,000 ppm range. This verifies that a significant fraction of the carbon in biomass is fully oxidized to CO₂. The variation in CO₂ readings indicates differences in kiln efficiency, fuel properties, and operating methods. Kilns utilizing dry, high-calorific-value biomass are more prone to achieving elevated combustion efficiency, hence resulting in increased CO₂ emissions (Bhattacharya et al., 2002). Descriptive statistics revealed that CO₂ concentrations varied between 4,715.63 – 91,785.71 ppm, with a mean of $30,913.5 \pm 19,373.41$ ppm (Figure 4.15). The significant fluctuation indicates considerable disparities in combustion efficiency among kilns, possibly influenced by site practices and measurements being obtained in a natural environment with no controls. The captured emission levels correspond with those documented in similar studies in South Asia and sub-Saharan Africa. A study in Asia showed CO₂ concentrations ranging from 40,000 to 80,000 ppm in traditional kilns utilizing hardwood fuel (Bhattacharya et al., 2002).

This study went ahead to analyze the CO₂ emissions over the entire 24-hour cycle (Figure 4.15) in three 8-hour periods. The examination of CO₂ emissions demonstrated clear patterns throughout the kiln burning cycle and their evolution in the entire cycle. In the first period, the median CO₂ concentration was approximately 25,000 - 28,000 ppm, with an IQR spanning roughly 15,000 - 40,000 ppm which demonstrate significant variability, indicated by a broad IQR and many outliers. This heterogeneity is likely due to diverse combustion circumstances when kilns shift from ignition to continuous burning, a feature previously seen in earlier research investigating the startup phase of traditional kilns (Demirbas, 2004).

During the intermediate period (Period 2), the median CO₂ emissions lowers and declined to around 22,000 ppm, and the IQR narrowed (approximately 18,000 - 30,000 ppm) and the diversity across kilns diminishes. Fewer outliers were noted in comparison to Period 1, indicating more consistent and uniform combustion across the kilns. This stability presumably corresponds with the phase of prolonged elevated temperatures, during which carbon monoxide produced earlier in the cycle is effectively oxidized into carbon dioxide. This trend corresponds with previous studies demonstrating that consistent kiln temperatures and enhanced airflow during peak operation improve combustion efficiency (Obernberger & Thek, 2004; Weyant et al., 2016).

During the last period (Period 3), the median CO₂ emissions rises to around 25,000 ppm, akin to Period 1, however with a more restricted IQR of 20,000 - 30,000 ppm. This decrease is likely due to the exhaustion of combustible materials and the cooling of kilns, which diminishes the pace and efficiency of combustion. Comparable findings have been documented in investigations of biomass-fueled kilns, indicating that emissions diminish as the firing cycle reaches its conclusion (Jayarathne et al., 2018). The study highlighted the variable characteristics of emissions in traditional brick kilns, indicating that the most stable CO₂ emissions transpire during the intermediate stage of the burning process. The results align with prior studies where it was observed that sustained combustion phases in biomass systems are generally linked to increased CO₂ concentrations resulting from effective oxidation (Bergman & Zerbe, 2008). These findings underscore the need of regulating operating parameters and fuel preparation, especially during the ignition and burnout stages, to reduce emission variability and enhance combustion efficiency.

5.3.1.2 Carbon Monoxide (CO)

CO emissions, albeit significantly lower than CO₂, exhibited substantial diversity among kilns, ranging from under 1,000 ppm to almost 4,000 ppm (*Figure 4.17*). This pattern indicated incomplete combustion resulting from inadequate oxygen delivery, elevated fuel moisture, or inappropriate kiln airflow. In traditional brick manufacturing kilns, where laborers are directly exposed to kiln fumes, carbon monoxide emissions constitute a considerable health hazard. The findings further indicate an inverse correlation between CO and CO₂: kilns with elevated CO₂ levels generally demonstrated reduced CO, whereas kilns with increased CO typically yielded lower CO₂. This connection indicated the level of combustion efficiency. Enhanced combustion efficiency promotes carbon oxidation to CO₂, hence diminishing CO production, while suboptimal combustion encourages incomplete oxidation and heightened CO levels. This emphasized the impact of biomass attributes, especially moisture content and calorific value, on emission patterns. Descriptive statistics revealed that CO concentrations varied from 273.08 – 3,898.84 ppm, with a mean of $1,821.859 \pm 951.6619$ ppm. The significant fluctuation indicated considerable disparities in combustion efficiency among kilns, possibly influenced by site practices and measurements being obtained in a natural environment with no controls. The captured emission levels correspond with those documented in similar studies in South Asia where a study in Delhi, India identified CO emissions from clamp kilns between 1,500 and 4,500 ppm in traditional kilns utilizing hardwood fuel (Guttikunda & Goel, 2013).

The differences in CO and CO₂ emissions among the studied kilns was affected by many critical factors such as fuel moisture content that is increased moisture diminishes combustion temperature and oxygen availability, promoting CO production and decreasing CO₂ emissions. In addition, various wood species exhibit differences in carbon content and combustibility, influencing their emission patterns. Species exhibiting elevated calorific values and reduced moisture generally produce diminished CO and augmented CO₂ emissions. The design and operation of traditional clamp kilns, characterized by uncontrolled airflow and inconsistent heating zones, result in incomplete combustion and increased CO emissions. Furthermore, elevated temperatures enhance combustion efficiency, resulting in increased CO₂ emissions and reduced CO emissions.

The distribution of CO emissions during three burning periods and their evolution over time were analyzed (*Figure 4.17*). During Period 1, the median concentration was around 1,800 - 2,000 ppm, accompanied by a somewhat broad IQR of approximately 1,200 - 2,000 ppm. Whiskers to 3,600 ppm, with many outliers noted, indicating significant fluctuation in emissions. This fluctuation is likely due to disparities in biomass fuel moisture content, kiln sealing efficacy, and inconsistent combustion during the ignition phase. Period 2 demonstrated a significant decrease in CO emissions, with a median of around 900 ppm and a more restricted IQR of 500 - 1,500 ppm. A reduced number of outliers signifies more uniformity among kilns. This phase is characterized by more stable combustion conditions wherein persistent high temperatures promote the oxidation of carbon monoxide to carbon dioxide. Finally, Period 3 had the highest median CO concentration at about 2,800 ppm and the broadest IQR of 600 - 3,600 ppm. Numerous severe outliers were seen, indicating substantial kiln-to-kiln variability. The increased emissions at this stage presumably indicate incomplete combustion during burnout and cooling, since remaining biomass is oxidized irregularly. The emission trend exhibits a U-shaped profile, characterized by elevated emissions during the ignition and burnout phases (Period 1 and 3) and decreased emissions during the intermediate firing stage (Period 2). This pattern highlights the significant impact of the combustion stage on emission behavior, consistent with the study's aim of evaluating the correlation between biomass fuel properties and emission profiles in traditional brick kilns.

These findings align with international research that underscores transitional times in combustion cycles as pivotal moments of increased CO production resulting from incomplete oxidation (Bergman & Zerbe, 2008; Khan et al., 2009). Comparable findings have been documented in sub-

Saharan Africa, where traditional clamp kilns demonstrate elevated CO emissions during ignition and burnout phases relative to steady burning periods, mostly because to suboptimal airflow, significant fluctuation in fuel characteristics, and inadequate combustion regulation (Figuroa et al., 2024). Kiln operating practices, such as pre-drying biomass, adjusting fuel feeding rates, and enhancing kiln sealant, are pivotal in mitigating incomplete combustion and decreasing total emissions. CO emissions, in contrast to CO₂, are situated close to the baseline with little variability; however, many kilns have significant CO outliers, indicating instances of incomplete combustion. There is an inverse link between CO and CO₂ emissions where kilns exhibiting greater CO₂ emissions often demonstrated lower CO emissions, indicating more efficient burning, whereas increased CO levels signify less efficient processes.

The assessment of CO and CO₂ emissions from biomass-fueled traditional brick kilns underscores the considerable environmental and health issues associated with these systems. Elevated CO emissions signify inadequate combustion efficiency and pose immediate health hazards, whereas CO₂ emissions measure the carbon footprint associated with brick manufacturing. Bhattacharya and Salam (2002) observed that elevated CO₂ levels often indicate more thorough burning, whereas diminished values frequently correlate with increased CO levels. Therefore, the elevated CO concentrations detected in the kilns signify poor combustion practices and can be attributable to the utilization of wet or unseasoned hardwood, poor kiln designs with inadequate air circulation within traditional kilns, uncontrolled burn cycles, and the absence of emissions mitigation measures such as chimneys. These findings highlight the necessity for enhanced kiln designs, better fuel utilization, and emission reduction techniques to foster sustainable brick production.

In conclusion, the calculated emissions of CO and CO₂ from traditional brick kilns pose serious issues for sustainable construction and the environmental. Similar studies indicated that yearly CO₂ emissions per cluster of kilns in the Greater Dhaka region, Bangladesh, ranged from 2.5 to 3.5 million kg, using both biomass and coal as fuel. This roughly corresponds with the 3.99 million kg of CO₂ projected in this study, illustrating similar emission loads in unregulated brick manufacturing kiln clusters (Guttikunda et al., 2012). This study's results show that there is significant emission potential of traditional biomass fueled kilns and indicate that Uganda's kilns may be more polluting per unit of fuel compared to similar systems in South Asia.

Adopting cleaner kiln technologies and utilizing alternative cleaner fuels may control emissions and enhance sustainability in the brick-making sector (UNDP, 2014). Furthermore, incorporating emission data into life cycle assessments (LCAs) of building materials can facilitate more environmentally sustainable decisions within Uganda's expanding construction industry, particularly for construction professionals and regulators seeking to comply with climate adaptation and mitigation policies.

5.3.2 Emission factors

The carbon mass balance approach was employed to calculate the emission factors of the pollutants in this study. The computation of emission factors from the 63 kilns revealed notable variability in both carbon monoxide (CO) and carbon dioxide (CO₂) emissions per kilogram of fuel consumed. The mean emission factor for CO was 18.81 ± 9.84 g/kg, with values ranging from 3 g/kg to 40 g/kg. For CO₂, the average fuel based emission factor was 500.82 ± 313.85 g/kg, with a range of 76 g/kg to 1,487 g/kg. These findings indicate substantial heterogeneity in emission factors, likely influenced by differences in kiln performance, fuel quality, and operational conditions. EF_{fuel} for CO₂ and CO among the traditional kilns, as observed in past literature from kilns in Nepal and Mexico, varied from 1526 g/kg to 1633 g/kg for CO₂ and 44.4 g/kg to 105.3 g/kg for CO (Nepal et al., 2019; Zavala et al., 2018). The average EF_{fuel} for CO₂ and CO in this study are low compared to previous research. This may be attributed to the fact that the fuel used in those studies was a combination of coal and other biomass fuels which increased its carbon content. The carbon content in coal is general higher than that biomass. Existing research has shown that compared with the combustion of hard coal, the CO₂ emissions can be reduced by approximately 93% when using biomass as fuel (Saidur et al., 2011). In addition, measurements of emissions in this study focused primarily on the burning stages as seen above and only included partial periods of the cooling stages. This would mean that a complete characterization of emissions for brick kilns would require the measurement of the entire brick burning cycle in order to accurately capture those EFs.

5.4 Influence of the Characteristic of Biomass on Emissions from Traditional Brick Kilns

For the third objective, the study sought to understand how the characteristics of biomass influenced the emissions during the brick production process. Having established the biomass characteristics, that is moisture content and calorific value, and the emissions associated with

traditional brick kilns, this study further examined whether there was a relationship between the characteristics and the emission levels. Understanding this relationship is essential for ensuring emission mitigation and recommending better alternative fuel sources. Correlation Analysis was utilized to show the strength and direction of relationships between biomass characteristics and emissions and regression analysis to show how much variation in emissions is explained by fuel properties.

5.4.1 Influence of Moisture Content on emissions

There was a positive and statistically significant, ($p < 0.05$) at 5% significance level, relationship between moisture content of hardwood fuel and CO emissions. The fitted line (*Figure 4.19*) shows that an increase in moisture content correlates with an increase in CO emissions, aligning with the statistically significant regression findings. This means that the higher the moisture content, the more incomplete combustion of wood resulting in high CO emissions. The regression model demonstrated statistical significance, $F(1,61) = 6.56$, $p = 0.013$, with a $R^2 = 0.1$, signifying that 10% of the variance in CO emissions is accounted for by moisture content. The regression coefficient was $\beta = 207.3$, $p < 0.05$, indicating that for each 1% rise in moisture content, CO emissions escalated by almost 207.3 ppm. The linear regression model (*equation 4.3*) was:

$$CO(ppm) = -1400.15 + 207.3017 \times \text{Moisture Content (\%)}$$

These findings align with Demirbaş's (2004) results, which highlighted that elevated moisture levels diminish combustion temperature and oxygen availability, resulting in incomplete oxidation of carbon molecules and thus increasing CO levels. Wet biomass also necessitates energy to remove internal moisture prior to ignition, thereby delaying full combustion and diminishing efficiency. Obernberger & Thek (2004) discovered that high moisture content in woody biomass leads to increased CO concentrations due to compromised flame stability and localized oxygen deficit. On the other hand, the relationship between moisture content and CO₂ implies that the moisture content does not significantly affect the levels of CO₂. The model lacked statistical significance at the 5% significance level, $F(1,61) = 0.88$, $p = 0.352$, $R^2 = 0.014$. The regression coefficient was $\beta = 1614.31$; however, there is insufficient evidence of a correlation between moisture content and CO₂ emissions.

There was a weak association between moisture content and CO₂ emissions, however, the data points were widely scattered, and the slope of the regression line was minimal (*Figure 4.20*). This corresponds with the regression findings, which lacked statistical significance at the 5% threshold. This relationship aligns with other studies that explain the limited impact of moisture content on CO₂ production. Literature noted that CO₂ emissions correlate more significantly with total carbon content in fuel and combustion efficiency than with the moisture content of the fuel (Oberberger & Thek, 2004). In summary, CO₂ results from full combustion, and although moisture might delay complete combustion, it does not reliably result in significant variations in total CO₂ concentration among kilns unless the combustion system is meticulously regulated.

5.4.2 Influence of Calorific Value on emissions

There was a negative correlation between calorific value and carbon monoxide emissions (*Figure 4.21*). As calorific value rises, CO emissions diminish, signifying that fuels with more energy content combust more thoroughly and cleanly. This visual pattern corroborates the regression outcome. This is well supported by existing literature which suggests that fuels with elevated calorific values burn more effectively, as opposed to generating intermediate products such as CO (Demirbas, 2004). It is also observed that high calorific value biomass diminishes unburnt hydrocarbons and carbon monoxide by reducing the residence time necessary for full combustion (Kumar et al., 2015).

A linear regression analysis was performed to evaluate the impact of biomass calorific value (MJ/kg) on carbon monoxide (CO) emissions. The model for carbon monoxide emissions was statistically significant, $F(1,61) = 10.62$, $p = 0.002$, with a R^2 of 0.15. This signifies that 15% of the variation in CO emissions is accounted for by calorific value. The regression coefficient was $\beta = -100.72$, indicating that a 1 MJ/kg increase in calorific value results in a reduction of roughly 100 ppm in CO emissions. The linear regression model (*equation 4.4*) was:

$$CO(ppm) = 3659.76 - 100.72 \times \text{CalorificValue (MJ/Kg)}$$

There was a negative association between CO₂ emissions and increasing calorific value (*Figure 4.22*). Nevertheless, the dispersion of the data points was broader, and the gradient was less pronounced. This may be attributed to CO₂ emissions being influenced more by the efficiency of combustion and the availability of oxygen than by the energy content of the fuel alone. Previous

research shows that CO₂ is a principal byproduct of full combustion, and that differences in kiln design, airflow, and operational methods may diminish the significance of fuel characteristics like calorific value (Nussbaumer, 2003). Therefore, fuels with more calorific value may not produce elevated CO₂ emissions if combustion conditions are inadequate.

The regression model for CO₂ was statistically significant at the 5% level ($p = 0.038$), however it had a lower R² of 0.07. This indicates a diminished correlation, with increased calorific values linked to decreased CO₂ emissions ($\beta = -1396.29$ ppm per MJ/kg). The linear regression model (*equation 4.5*) was:

$$CO_2(ppm) = 56391.59 - 1396.29 \times \text{Calorific Value (MJ/Kg)}$$

The study, therefore, concludes that biomass with elevated energy content facilitates more efficient burning, hence decreasing emissions of both CO and CO₂, with a more significant impact on CO emissions.

5.4.3 Influence of fuel quantity on emissions

Despite the dispersion of the data points being broader, and the gradient less pronounced, there was a negative association between CO emissions and increasing fuel (*Figure 4.23*). A linear regression analysis was conducted to ascertain if the quantity of fuel predicted carbon monoxide emissions. The model demonstrated statistical significance, $F(1, 61) = 4.56$, $p = 0.037$, with fuel quantity accounting for roughly 7% of the variation in CO emissions ($R^2 = .070$). The quantity of fuel was a negative predictor of carbon monoxide emissions, suggesting that an increase in fuel quantity correlated with reduced CO levels. The linear regression model (*equation 4.6*) was:

$$CO(ppm) = 2445.23 - 86.9 \times \text{Fuel Amount (t)}$$

There was a slightly positive association between CO₂ emissions and increasing fuel quantity as shown in the findings (*Figure 4.24*). Nevertheless, the dispersion of the data points was broader, and the gradient was less pronounced. On the other hand, simple linear regression was performed to assess the predictive relationship between fuel quantity and CO₂ emissions. The model lacked statistical significance, $F(1, 61) = 2.06$, $p = 0.156$, suggesting that fuel quantity was not a dependable predictor of CO₂ emissions. The coefficient of determination indicated that fuel quantity accounted for just 3.3% of the variation in CO₂ emissions ($R^2 = 0.033$). However, it indicated a tendency for CO₂ levels to rise with increased fuel quantities, lacking statistical

validation. The results indicate a lack of substantial evidence for a correlation between fuel quantity and CO₂ emissions in this sample. This may be attributed to the fact that biomass ingests carbon dioxide (CO₂) during its growth/ developing period and discharges it during ignition in kilns. In this way, biomass helps to recycle carbon dioxide (CO₂) from the atmosphere and doesn't contribute to any other emissions (GHG) such as CO or CO₂. Additionally, biomass releases the same amount of CO₂ into the atmosphere during growth as it does during burning, which is known as "carbon neutral" in science (Asif et al., 2021; Sivabalan et al., 2021). This refers to achieving a state where an entity that produces carbon emissions to the earth's atmosphere removes the same volume of carbon emissions from it (International Finance Corporation, 2023). In conclusion, the quantity of fuel used in traditional kilns has no major implication or impact on the amount of emissions released into the atmosphere. This, however, does not overlook the need for construction professionals to advocate for the use of properly dried, high calorific value hardwood fuel by kiln operators during the making of bricks.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study aimed to investigate the impact of biomass properties on gaseous emissions, especially carbon monoxide (CO) and carbon dioxide (CO₂), during traditional brick manufacture in Uganda's informal construction industry. The study utilized field data from 63 traditional kilns and analyzed biomass fuel samples to achieve three objectives: characterizing the biomass used, quantifying emissions, and analyzing the relationship between biomass characteristics and emissions. The principal findings derived from each target are detailed below;

The first objective was intended to characterize the biomass fuel used in burnt brick production. It identified that hardwood biomass, often derived from eucalyptus and other indigenous tree species, was the predominant fuel type utilized in the 63 studied kilns. The moisture content fluctuated between 11% and 18%, but the calorific values ranged from 11 MJ/Kg to 27 MJ/Kg. The fuel quantities (in tonnes) utilized among the sampled traditional brick kilns was also analyzed which ranged from 2.3 to 12.65 tonnes. There was a negative association between moisture content in biomass and its calorific value. Furthermore, there was a negative relationship between fuel quantity used and moisture content. On the other hand, there was no significant association between fuel amount used and calorific value. The findings correspond with the studies that identified the change in biomass properties stemming from changes in tree species, drying methodologies, and storage conditions. The higher moisture levels indicate insufficient pre-combustion fuel preparation, a significant factor in poor kiln efficiency and increased emissions.

The second objective aimed to determine the emissions associated with the biomass used in traditional brick kilns. It showed significant CO and CO₂ emissions, with CO concentrations ranging between 273 ppm and 3,899 ppm, and CO₂ concentrations ranging from 4,716 ppm to 91,786 ppm. These results, although within anticipated limits for biomass combustion, signify inefficient and erratic combustion processes. NO and NO_x, on the other hand, were present in negligible amounts due to the low nitrogen content in biomass wood fuel. The increased CO levels indicate incomplete combustion, particularly in kilns utilizing wetter hardwood or insufficient air supply. Furthermore, the conversion of ppm to kg provided a more thorough understanding of pollution severity through understanding the emission factors. The mean fuel based emission factor for CO was 18.81 ± 9.84 g/kg while that for CO₂ was 500.82 ± 313.85 g/kg which were much

lower than those from coal fueled kilns in other countries in Asia and Mexico. This conversion, adhering to IPCC (2006), facilitated the reporting of emission factors in recognized units, an essential advancement in including traditional kiln emissions into comprehensive environmental inventory.

The third objective sought to understand how the characteristics of biomass influenced the emissions during the brick production process. It established that moisture content and calorific value greatly affect CO emissions, but only calorific value had an impact on CO₂ emissions. This indicates that fuels with greater moisture and lower energy yield increased the production of incomplete combustion byproducts. Moisture content did not substantially predict CO₂ emissions, evidenced by a statistically insignificant regression model showing that CO₂ production is more significantly affected by the completeness of combustion and airflow dynamics than by moisture content alone. CO emissions evidently decreased with increased calorific values, but carbon dioxide exhibited an inconsistent pattern. Finally, there was no major association between fuel quantity used and emissions due to the entire process being carbon neutral.

The study's findings have direct implications for the country's construction industry given that bricks are still the most common building material in Uganda. From the results, inefficient combustion caused by high moisture content and improperly prepared biomass fuels results in high CO emissions and irregular CO₂ outputs, which are a reflection of inefficient kilns and excessive fuel consumption. This undermines the larger objectives of sustainable building practices by increasing production costs and increasing the environmental impact on the construction sector. By emphasizing the connection between biomass properties, combustion efficiency, and emissions, this study highlights the need for major interventions that would improve building material quality and affordability while also bringing Uganda's construction sector into line with international initiatives for low-carbon, greener development.

6.2 Recommendations

From the study's findings, the following recommendations and strategies can be employed to improve brick production using traditional kilns:

6.2.1 Strengthen Training on Efficient Kiln Operation

Targeted training programs should be implemented to educate kiln operators in efficient combustion practices, including proper fuel preparation, stacking methods, airflow control, and firing cycles. Uganda Industrial Research Institute (UIRI) and Technical Vocational Education and Training (TVET) institutions already provide artisan training, allowing these modules to be integrated with minimal additional resources.

6.2.2 Develop and Promote Low-Cost Improved Kiln Designs

Improved kiln designs, such as modified clamp kilns, should be developed using locally available materials and disseminated to brickmaking communities. Local feasibility is high, as research institutions already innovate in stove and kiln technologies that can be adapted for traditional brick production.

6.2.3 Strengthen Local Emissions Monitoring

Periodic emission monitoring should be incorporated into district environmental inspections to track kiln performance and guide policy interventions. This is achievable because District Environment Officers already conduct routine compliance checks, and emissions monitoring can be added with minimal procedural changes.

6.2.4 Provide Financial Incentives for Cleaner Production

It is recommended that financial incentives, such as low-interest loans and small grants, be established to support kiln upgrades, biomass drying structures, and improved firing practices. Existing government programs such as the Parish Development Model (PDM) offer frameworks that can accommodate such support.

6.2.5 Establish Community-Based Biomass Drying Yards

Shared biomass drying yards should be established to ensure that fuelwood is properly dried before use. These yards may consist of simple raised racks and shelters to promote controlled drying. This approach is realistic because many brickmaking communities already operate collectively, making shared infrastructure both manageable and affordable through small user contributions.

6.3 Areas for further research

The scope of this investigation was restricted to monitoring emissions in an uncontrolled setting where it was unable to completely control changes in wind speed, ambient temperature, and nearby activity. Uncertainties and approximations were unavoidably introduced into the recorded data by these outside influences. Future studies could use controlled experimental setups, like laboratory-scale kilns or semi-controlled field trials, to increase the validity and reliability of results in light of this constraint. Researchers would be able to isolate particular factors and methodically assess how these affect emission patterns through controlled trials.

Secondly, fuel factors, specifically the properties of biomass used in burning clamp kilns, were the main focus of the current study. Although this offers valuable information, other moderating factors also have a significant impact on emissions in traditional brick kilns. Therefore, more research should look into how differences in emission concentrations are caused by brick properties, kiln size, burning mode (batch versus continuous fire), and airflow management (ventilation design, draft control, and stacking arrangements). The best kiln designs or changes that reduce emissions without appreciably raising production costs may be found with the use of such research.

Furthermore, future studies should develop and validate a predictive biomass-demand model that estimates the fuel required for various kiln workloads by integrating key variables such as biomass characteristics, kiln size, combustion efficiency, and operator practices. Such a model would enable more accurate planning of fuel needs, support efficiency improvements, and provide a valuable decision-making tool for kiln operators and policymakers seeking to optimize biomass use and reduce emissions.

Future research should also integrate in-situ flue gas monitoring with chemical profiling and mineralogical analysis of fired bricks to characterize dehydration, oxidation, de-carbonation and vitrification reactions in traditional Ugandan clamp kilns.

Lastly, a more thorough grasp of the variations in kiln performance and environmental effects may be provided by longitudinal research that monitor emissions over several fire cycles, seasons, or geographical areas. These studies, when combined with life cycle assessments (LCA) and cost-benefit evaluations, would give industry stakeholders, kiln owners, and legislators evidence-based suggestions for moving toward more environmentally friendly brick production methods.

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APPENDICES

8.1 INSTRUMENTS/ TOOLS

8.1.1 Observation Checklist

7/3/25, 8:00 PM

MUK-MCM-BIOMASS &GHG Emissions Data Collection Tool: December 2024 - May 2025

7/3/25, 8:00 PM

MUK-MCM-BIOMASS &GHG Emissions Data Collection Tool: December 2024 - May 2025

MUK-MCM-BIOMASS &GHG Emissions Data Collection Tool: December 2024 - May 2025

This form is to be used for the collection of field data from sites where brick making is being done.

* Indicates required question

1. Email *

GENERAL INFORMATION

2. Location of Site *

3. Kiln No. *

KILN INFORMATION

4. Describe Kiln Type

FUEL/BIOMASS ASSESSMENT

5. Biomass Type

6. Species or Category

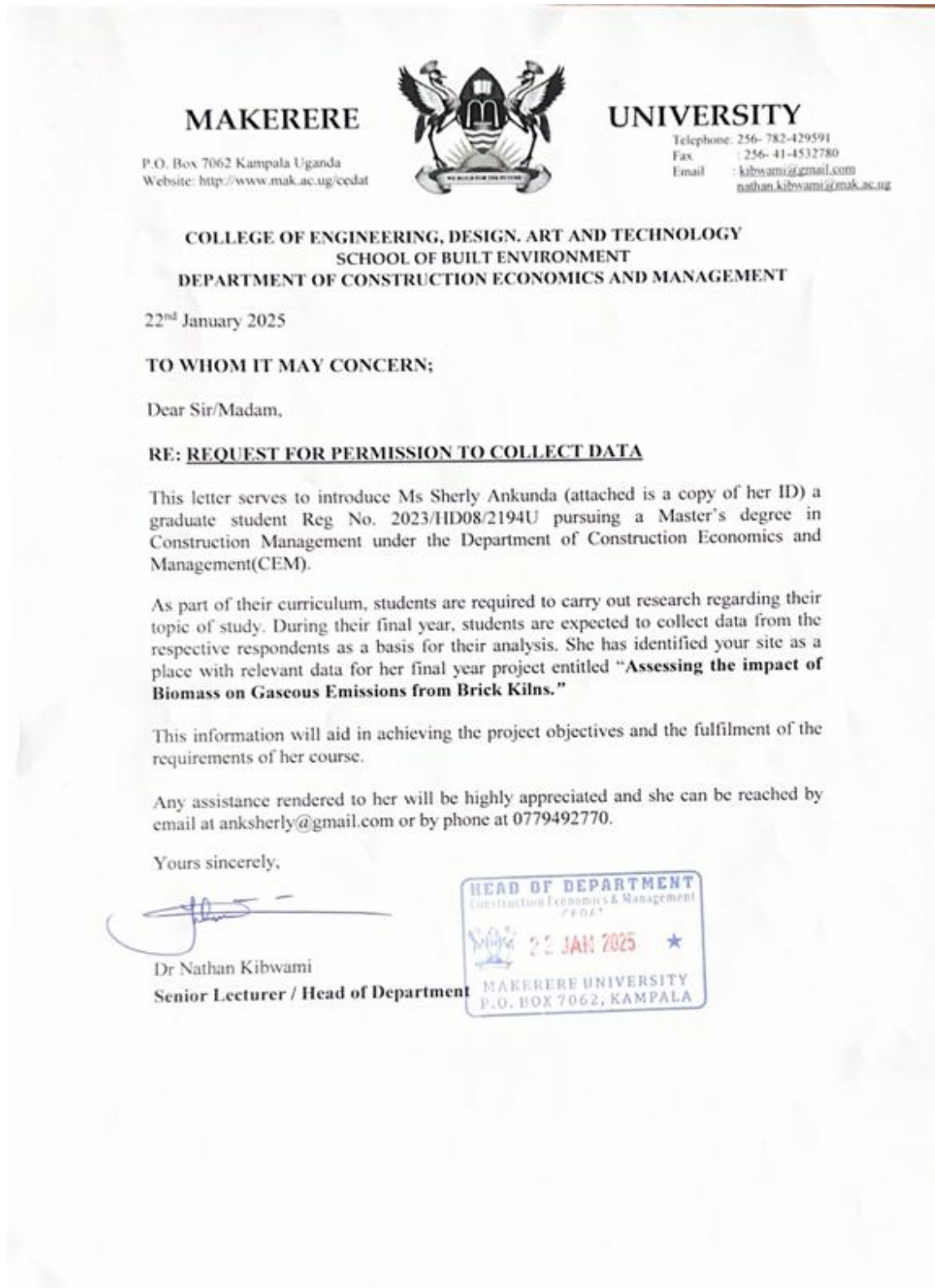
7. Source of Biomass

8. Any other information from kiln operators that may be of importance to the research.

https://docs.google.com/forms/d/1t1XEduWccsT6sA3HBDJYd-fezb90AbQyjbMggUKGrik/edit

1/3

8.2 INTRODUCTORY LETTER



8.3 EXPERIMENTAL PROCEDURES

8.3.1 Emission Measurement

Equipment:

IMR 1400 Portable Flue Gas Analyzer

Procedure:

- a. The IMR 1400 analyzer was initially inspected to confirm that the battery was completely charged and the device was functioning correctly.
- b. The gadget was activated and let to complete its self-calibration and zeroing procedure in uncontaminated ambient air.
- c. The suitable fuel type (i.e. wood) was chosen from the analyzer's internal fuel database to guarantee precise computations.
- d. The sample probe was thereafter put into the flux chamber set up at a representative location, establishing a secure seal to prevent ambient air contamination.
- e. The gas sample was extracted via the probe into the analyzer, where sensors quantified the amounts of gases including O₂, CO, CO₂, and other pertinent factors.
- f. The measurements were presented on the analyzer screen in real time and let to stabilize prior to recording.
- g. Measurements were conducted at various phases of the kiln burning process to document emission fluctuations.
- h. Upon completion of measurements, the probe was extracted, the pump was switched off, and the analyzer was let to purge with ambient air.
- i. The analyzer was thereafter powered off, and the probe and filters were cleaned and stored in accordance with the manufacturer's instructions.

8.3.2 Moisture Content

Equipment:

Testo 606-1 moisture meter

Procedure:

- a. The equipment was initially checked for sufficient battery level and operational functionality.
- b. The equipment was then activated, and the relevant material category (i.e. wood) was chosen using the function keys.

- c. The meter's two penetration electrodes were thereafter put firmly into the prepared sample to guarantee optimal contact with the substance.
- d. The apparatus quantified the electrical resistance between the electrodes, which corresponds with the moisture content of the material.
- e. The moisture content result was thereafter presented on the screen as a percentage by weight (%).
- f. The measurement was conducted at several locations inside the sample, and the mean moisture content was calculated for precision.
- g. After measurement, the electrodes were sanitized, and the equipment was deactivated and securely stored.

8.3.3 Calorific Value

Equipment:

Oxygen bomb calorimeter

Procedure:

- a. The bomb calorimeter was initially calibrated with standard benzoic acid pellets to ascertain the system's energy equivalent.
- b. The test sample was prepared by drying, milling, and grinding to get a fine and uniform powder.
- c. Approximately one gram of the material was compacted into a pellet with a pellet press.
- d. The sample pellet was positioned in a clean crucible or capsule, which was thereafter inserted between the igniting electrodes.
- e. A calibrated length of fuse wire was linked between the electrodes, assuring contact with the sample, and a short segment of cotton thread was affixed to facilitate ignition.
- f. The bomb head was meticulously assembled, properly sealed with the O-ring, and firmly tightened.
- g. Oxygen was introduced into the bomb at a pressure of 30 bars to guarantee full combustion.
- h. The charged bomb was thereafter positioned inside the calorimeter bucket carrying a specified quantity of distilled water (about 2 liters).
- i. The calorimeter cover was secured in place, and the stirrer along with the temperature sensors were activated.

- j. The calorimeter was activated, and the sample was ignited, resulting in combustion within the sealed bomb vessel.
- k. The increase in water temperature was recorded automatically, and the calorific value of the sample was exhibited by the calorimeter system.

8.4 PHOTOGRAPHS

Transect Walks to Obtain Preliminary Sites



Brick Mould



Drying of Stacked Green Mud Bricks Before Burning



Moulded Mud Bricks Before Stacking



Biomass Fuel Used to Burn the Kiln



Gas Analyzer Measuring Emissions in Flux Chamber



Excavated Pit to Obtain Mud



Firing of Mud Kiln



8.5 SAMPLE FRAME

Table 8.1: Sample Frame (Source; Author)

	District	Municipality		Brick Making Site	Google Map Coordinates	No of Kilns	
A	Wakiso	Kira	1	Kijjabijjo - Nakwero	0°28'33.90"N, 32°39'19.43"E	9	
			2	Nangabo (Gayaza - Matuga)	0°26'38.90"N, 32°35'43.84"E		
			3	Potential site - Mairye	0°32'55.45"N, 32°40'24.39"E		
			4	Mawule	0°27'59.27"N, 32°34'48.94"E		
			5	Kabanyolo, Greenfield Rd	0°27'57.10"N, 32°36'3.27"E		
			6	Homisdallen Site	0°27'16.65"N, 32°35'57.00"E		
			7	Namayina Jolwe	0°28'54.77"N, 32°37'23.80"E		
			Entebbe	8	Kaga -	0°11'34.26"N, 32°28'52.16"E	11
				9	Sissa	0°10'35.53"N, 32°29'4.32"E	
				10	Nakirama	0°14'53.89"N, 32°30'49.11"E	
				11	Garuga	0° 5'3.35"N, 32°33'27.38"E	
				12	Nakawuka I	0°10'14.31"N, 32°27'23.80"E	
				13	Jungo - Nakawuka	0°10'33.90"N, 32°26'51.23"E	
				14	Nakawuka II	0°10'23.07"N, 32°27'11.23"E	
				15	Nkumba	0° 4'38.91"N, 32°30'5.73"E	
				16	Nalugala Estate, Great Tabernacle	0° 5'16.53"N, 32°32'4.93"E	
				17	Express way - Kampala, Entebbe	0°13'40.00"N, 32°31'42.65"E	
				18	Entebbe -Kawuku- Nakawuka Rd	0°10'54.28"N, 32°28'36.22"E	
			Nansana	19	Kawanda A	0°24'53.04"N, 32°31'4.66"E	12
				20	Kawanda Site B	0°24'59.25"N, 32°31'12.87"E	
				21	Homisdallen - Greenfield Rd	0°27'16.68"N, 32°35'56.98"E	
				22	Makenke - Kabanyolo	0°27'58.66"N, 32°36'3.41"E	

	District	Municipality		Brick Making Site	Google Map Coordinates	No of Kilns
			23	Lutete - Busukuma	0°33'31.97"N, 32°34'56.82"E	
			24	Nkowe	0°24'26.02"N, 32°26'20.48"E	
			25	Bukalango	0°24'52.10"N, 32°24'27.57"E	
B	Mukono	Mukono	26	Muga Rc - Kigunga	0°22'43.78"N, 32°43'46.47"E	30
			27	Dandira	0°20'14.87"N, 32°46'32.66"E	
			28	Nyenje 1	0°24'40.91"N, 32°44'4.44"E	
			29	Nyenje II	0°24'48.82"N, 32°44'8.84"E	
			30	Sonde Connect Africa Voc. Inst.	0°24'0.22"N, 32°42'24.55"E	
			31	Bukerere (True Vine Evangelical)	0°25'4.63"N, 32°43'10.38"E	
			32	Bajjo	0°23'25.43"N, 32°42'51.77"E	
			33	Bajjo II	0°23'49.35"N, 32°43'5.17"E	
			34	Seeta Bajjo - Jabulani Catering	0°23'22.84"N, 32°43'31.83"E	
			35	Bajjo - Canaan Estate I	0°24'4.64"N, 32°43'17.34"E	
			36	Bajjo - Canaan Estate II	0°24'16.24"N, 32°43'21.51"E	
			37	Bajjo (Near Praise Apartments)	0°23'41.79"N, 32°43'29.41"E	
			38	Nsube (Daks Courier limited)	0°19'13.68"N, 32°45'0.62"E	
			39	Nkonge	0°29'21.74"N, 32°43'47.04"E	
			40	Kasaa	0°26'36.39"N, 32°43'9.53"E	
			41	Kasaii	0°26'6.81"N, 32°43'8.88"E	
			42	Kasa	0°25'51.74"N, 32°43'39.64"E	
			43	Kasaayi	0°25'33.52"N, 32°44'1.95"E	
			44	Nyenje - Kasayi	0°25'4.37"N, 32°44'7.18"E	
			45	Kasayi - Nyenje	0°25'14.83"N, 32°43'45.19"E	
			46	Bukerere - Kiyunga	0°27'56.27"N, 32°44'37.80"E	

	District	Municipality		Brick Making Site	Google Map Coordinates	No of Kilns
C	Mpigi	Mpigi	47	Kkongge	0°16'54.37"N, 32°19'32.00"E	9
			48	Jandira - Katende	0°13'5.39"N, 32°24'2.89"E	
			49	Nama	0°16'38.04"N, 32°21'30.78"E	
			50	Nama, Nama Catholic Church	0°17'12.03"N, 32°20'52.69"E	
			51	Sokolo	0°12'14.19"N, 32°25'16.90"E	
			52	Sokolo - Site II	0°12'22.40"N, 32°25'25.15"E	
			53	Nsangi	0°16'54.37"N, 32°19'32.00"E	
D	Kampala	KCCA	54	Kyebando	0°21'33.34"N, 32°35'49.89"E	2
	TOTAL					73

8.6 DETAILED TABLES SHOWING THE ANALYSIS OF RESULTS

Table 8.2: Summary Emission Data from 63 Kilns (Source; Primary Data)

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO ₂ (%)	CO ₂ (ppm)	NO (ppm)	NO _x (ppm)
1	MMU-CY-K1	Mukono	Eucalyptus	15.844	18.5	1,725.40	1.40	13,951.08	6.30	817.08
2	MMU-CY-K2	Mukono	Eucalyptus	17.14	19.8	2,003.80	2.52	25,214.48	4.82	580.95
3	KMU-MD-K1	Mukono	Mango and jackfruit, eucalyptus	15.945	19.4	1,912.13	0.59	5,881.90	8.56	997.84
4	KKR-MD-K2	Wakiso	Mango and eucalyptus	16.569	16.5	3,898.84	1.13	11,261.36	13.89	917.72
5	NNG-CY-K1	Wakiso	Mango , Jackfruit and eucalyptus	16.475	16.4	3,695.07	9.18	91,785.71	45.27	173.70
6	KSM-CY-K1	Mukono	Mango , Jackfruit and eucalyptus	13.231	17.5	1,176.77	2.54	25,411.76	8.75	648.80
7	KSM-CY-K2	Mukono	Mango , Jackfruit and eucalyptus	14.598	18.1	1,402.65	0.61	6,080.60	2.86	992.03
8	KSM-CY-K3	Mukono	Mango , Jackfruit and eucalyptus	14.007	19.1	854.43	0.47	4,715.63	2.39	979.58
9	KSM-CY-K4	Mukono	Mango , Jackfruit and eucalyptus	11.855	22.4	982.28	0.72	7,165.00	3.91	972.57

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO₂ (%)	CO₂ (ppm)	NO (ppm)	NO_x (ppm)
10	KKI-CY-K1	Wakiso	Mango , Jackfruit and eucalyptus	16.401	15.46	3,659.33	6.75	67,462.30	20.02	202.84
11	KKI-CY-K2	Wakiso	Mango , Jackfruit and eucalyptus	16.375	14.6	3,107.65	5.94	59,403.33	15.16	233.68
12	KKI-CY-K3	Wakiso	Mango , Jackfruit and eucalyptus	12.441	22.4	2,576.85	6.20	62,015.00	15.67	223.61
13	KKI-CY-K4	Wakiso	Mango , Jackfruit and eucalyptus	17.195	20.1	2,233.31	4.89	48,898.33	12.52	274.92
14	KKI-CY-K5	Wakiso	Mango , Jackfruit and eucalyptus	16.386	15.4	3,285.48	8.79	87,880.83	20.08	127.41
15	KKI-CY-K6	Wakiso	Mango , Jackfruit and eucalyptus	14.597	18.1	1,281.23	5.83	58,295.49	13.33	208.45
16	KMM-MD-K1	Mukono	Eucalyptus	15.845	18.6	1,858.08	1.47	14,670.16	4.96	496.34
17	KMM-MD-K2	Mukono	Eucalyptus	17.443	11.4	2,304.44	1.52	15,247.15	3.04	879.57
18	KMM-MD-K3	Mukono	Eucalyptus	17.377	20.2	2,247.17	2.16	21,561.11	3.90	623.89
19	KMM-MD-K4	Mukono	Eucalyptus	17.32	12.4	2,461.30	2.75	27,478.63	4.62	493.02
20	BUK-CY-K1	Wakiso	Eucalyptus	16.213	20.5	403.71	0.84	8,384.13	1.45	987.50

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO ₂ (%)	CO ₂ (ppm)	NO (ppm)	NO _x (ppm)
21	KLO-CY-K1	Wakiso	Mugavu and Avocado	16.375	14.4	2,814.90	2.03	20,327.27	9.49	656.48
22	KLO-CY-K2	Wakiso	Mugavu and Avocado	13.092	21.1	2,691.76	2.62	26,229.37	12.47	511.46
23	KLO-CY-K3	Mukono	Mugavu and Avocado	14.525	25	1,145.81	1.23	12,297.62	7.85	963.22
24	MBU-CY-K1	Wakiso	Muvule, Jackfruit and Musizi	15.149	19	760.56	2.30	22,996.24	9.63	595.16
25	ABS-CY-K1	Wakiso	Mango and Jackfruit	14.282	25.1	2,517.04	2.74	27,421.43	7.46	480.83
26	NAM-CY-K1	Wakiso	Eucalyptus	14.427	21.1	2,308.82	3.33	33,301.25	19.19	566.34
27	NAM-CY-K2	Wakiso	Eucalyptus	17.184	19.9	2,195.77	3.93	39,266.17	7.09	399.37
28	NAM-CY-K3	Wakiso	Eucalyptus	14.689	18.2	1,520.54	3.34	33,360.84	5.47	472.17
29	NAM-CY-K4	Wakiso	Eucalyptus	15.724	21.4	648.04	2.53	25,260.87	1.97	511.39
30	NAM-CY-K5	Wakiso	Eucalyptus	16.481	16.5	3,734.54	2.82	28,182.46	6.76	458.80
31	KAS-CY-K2	Wakiso	Eucalyptus and Mutuba	14.0072	19.2	932.84	1.31	13,063.89	4.12	585.52
32	NKI-MD-K1	Kampala	Avacado and Mutuba	17.298	12.7	2,393.16	5.40	53,951.89	21.19	254.54
33	NKI-MD-K2	Kampala	Avacado and Mutuba	17.302	13	2,446.72	4.43	44,349.62	10.50	446.57

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO ₂ (%)	CO ₂ (ppm)	NO (ppm)	NO _x (ppm)
34	BNA-MD-K1	Wakiso	Mugavu , Avocado and Eucalyptus	14.006	17.8	1,190.04	2.56	25,593.33	8.55	664.95
35	BNA-MD-K2	Wakiso	Mugavu , Avocado and Eucalyptus	16.291	12.2	566.55	1.66	16,583.03	5.36	795.67
36	BUY-CY-K1	Wakiso	Mugavu,Mvule and Mango	11.955	20.6	1,973.56	3.33	33,315.53	10.55	398.25
37	KYE-CY-K1	Mukono	Mugavu,Mvule and Mango	14.536	18.1	1,219.45	3.63	36,331.03	8.69	369.91
38	KIW-CY-K1	Wakiso	Mugavu,Mvule and Mango	15.148	18.4	1,667.84	4.47	44,694.57	8.06	271.07
39	KAZ-CY-K1	Wakiso	Mugavu,Mvule and Mango	14.536	17.4	1,148.35	6.15	61,459.24	12.64	183.21
40	KYA-CY-K1	Wakiso	Mugavu,Mvule and Mango	15.831	18.9	748.97	6.35	63,468.46	12.70	177.03
41	KYA-CY-K2	Wakiso	Mugavu,Mvule and Mango	14.339	25.1	1,024.39	5.51	55,100.00	9.24	211.95
42	SEN-CY-K1	Wakiso	Eucalyptus	15.338	19	797.94	2.05	20,503.28	3.32	689.54
43	KAW-CY-K1	Wakiso	Mugavu	13.081	13.1	2,585.27	1.81	18,127.62	7.97	758.72
44	SEN-CY-K3	Wakiso	Mugavu	16.471	15.6	3,663.80	2.96	29,619.88	9.76	451.87
45	SEN-CY-K4	Wakiso	Mugavu	16.364	13.2	586.29	2.49	24,874.05	5.27	558.82

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO ₂ (%)	CO ₂ (ppm)	NO (ppm)	NO _x (ppm)
46	KKI-CY-K1	Wakiso	Mugavu	14.659	18.2	1,480.93	1.85	18,542.64	8.53	727.23
47	NAF-CY-K1	Mukono	Eucalyptus	16.384	15.1	3,154.93	2.63	26,268.34	5.73	496.23
48	MPM-CY-K1	Mukono	Eucalyptus	17.4	11.2	2,268.25	2.23	22,339.58	4.40	593.61
49	KLO-CY-K4	Wakiso	Mugavu and Avocado	15.007	18.3	1,634.98	1.62	16,233.79	8.02	829.07
50	NNG-CY-K2	Mukono	Eucalyptus and Mugavu	17.259	11.7	2,355.40	2.64	26,439.83	10.87	583.46
51	SEN-CY-K5	Wakiso	Mugavu	16.002	20.3	273.08	1.04	10,425.98	2.67	969.57
52	MMM-CY-K1	Wakiso	Muvule, Jackfruit and Musizi	14.448	26.2	1,075.81	4.70	47,036.37	9.35	300.61
53	SEN-CY-K6	Wakiso	Mugavu	16.669	19.4	2,560.14	3.93	39,331.08	3.93	494.85
54	SEN-CY-K7	Wakiso	Eucalyptus and Muvule	14.008	26.4	969.21	2.14	21,410.55	2.81	651.68
55	SEN-CY-K8	Wakiso	Eucalyptus	17.15	19.8	2,064.53	2.72	27,153.65	7.43	507.45
56	SEM-CY-K1	Wakiso	Mugavu	15.735	19.3	679.36	1.97	19,727.12	4.81	664.90
57	MKI-CY-K1	Wakiso	Mugavu	14.728	18.2	1,626.42	2.18	21,775.89	7.34	612.86
58	MKA-CY-K1	Wakiso	Mugavu	17.286	12	2,360.71	5.57	55,700.00	13.82	213.39
59	NMK-CY-K1	Mukono	Mango and avocado	16.274	21.1	505.54	1.12	11,161.61	2.06	929.73

NO.	KILN CODE	DISTRICT	FUEL SPECIES	MOISTURE CONTENT (%)	CALORIFIC VALUE (mj/kg)	CO (ppm)	CO₂ (%)	CO₂ (ppm)	NO (ppm)	NO_x (ppm)
60	NAM-CY-K6	Wakiso	Mango, Jackfruit and eucalyptus	15.859	18.8	1,874.59	3.63	36,277.73	8.83	459.97
61	ABU-CY-K1	Mpigi	Mango and Jackfruit	17.245	20.2	2,246.50	2.78	27,756.68	7.77	474.14
62	SEN-CY-K9	Wakiso	Mugavu	15.648	21.3	624.29	2.82	28,224.43	7.47	505.62
63	BUJ-CY-K1	Mpigi	Avacado and Eucalyptus	15.734	19.2	669.60	1.93	19,302.23	6.33	736.30

Table 8.3: Emission factors of 63 kilns (Source; Primary Data)

KILN CODE	CO (ppm)	CO₂ (ppm)	FUEL AMOUNT (kg)	FUEL AMOUNT (tonnes)	NO. BRICKS	EF-CO (g/kg)	EF-CO₂ (g/kg)
MMU-CY-K1	1,725.40	13,951.08	5,750	5.75	10,000	18	226
MMU-CY-K2	2,003.80	25,214.48	5,750	5.75	10,000	21	408
KMU-MD-K1	1,912.13	5,881.90	5,750	5.75	10,000	20	95
KKR-MD-K2	3,898.84	11,261.36	5,750	5.75	10,000	40	182
NNG-CY-K1	3,695.07	91,785.71	11,500	11.50	20,000	38	1,487
KSM-CY-K1	1,176.77	25,411.76	11,500	11.50	20,000	12	412
KSM-CY-K2	1,402.65	6,080.60	11,500	11.50	20,000	14	99
KSM-CY-K3	854.43	4,715.63	11,500	11.50	20,000	9	76
KSM-CY-K4	982.28	7,165.00	11,500	11.50	20,000	10	116
KKI-CY-K1	3,659.33	67,462.30	5,750	5.75	12,000	38	1,093
KKI-CY-K2	3,107.65	59,403.33	5,750	5.75	12,000	32	962
KKI-CY-K3	2,576.85	62,015.00	5,750	5.75	12,000	27	1,005
KKI-CY-K4	2,233.31	48,898.33	5,750	5.75	12,000	23	792
KKI-CY-K5	3,285.48	87,880.83	5,750	5.75	12,000	34	1,424
KKI-CY-K6	1,281.23	58,295.49	5,750	5.75	12,000	13	944
KMM-MD-K1	1,858.08	14,670.16	5,750	5.75	12,000	19	238
KMM-MD-K2	2,304.44	15,247.15	5,750	5.75	12,000	24	247
KMM-MD-K3	2,247.17	21,561.11	5,750	5.75	12,000	23	349
KMM-MD-K4	2,461.30	27,478.63	5,750	5.75	12,000	25	445
BUK-CY-K1	403.71	8,384.13	5,750	5.75	12,000	4	136
KLO-CY-K1	2,814.90	20,327.27	5,750	5.75	13,000	29	329
KLO-CY-K2	2,691.76	26,229.37	5,750	5.75	13,000	28	425
KLO-CY-K3	1,145.81	12,297.62	5,750	5.75	13,000	12	199
MBU-CY-K1	760.56	22,996.24	11,500	11.50	23,000	8	373
ABS-CY-K1	2,517.04	27,421.43	3,450	3.45	7,000	26	444
NAM-CY-K1	2,308.82	33,301.25	5,750	5.75	10,000	24	539
NAM-CY-K2	2,195.77	39,266.17	5,750	5.75	10,000	23	636
NAM-CY-K3	1,520.54	33,360.84	5,750	5.75	10,000	16	540
NAM-CY-K4	648.04	25,260.87	5,750	5.75	10,000	7	409
NAM-CY-K5	3,734.54	28,182.46	5,750	5.75	10,000	39	457
KAS-CY-K2	932.84	13,063.89	11,500	11.50	20,000	10	212
NKI-MD-K1	2,393.16	53,951.89	11,500	11.50	20,000	25	874

KILN CODE	CO (ppm)	CO₂ (ppm)	FUEL AMOUNT (kg)	FUEL AMOUNT (tonnes)	NO. BRICKS	EF-CO (g/kg)	EF-CO₂ (g/kg)
NKI-MD-K2	2,446.72	44,349.62	11,500	11.50	20,000	25	718
BNA-MD-K1	1,190.04	25,593.33	12,650	12.65	30,000	12	415
BNA-MD-K2	566.55	16,583.03	12,650	12.65	30,000	6	269
BUY-CY-K1	1,973.56	33,315.53	11,500	11.50	30,000	20	540
KYE-CY-K1	1,219.45	36,331.03	11,500	11.50	30,000	13	589
KIW-CY-K1	1,667.84	44,694.57	11,500	11.50	30,000	17	724
KAZ-CY-K1	1,148.35	61,459.24	11,500	11.50	30,000	12	996
KYA-CY-K1	748.97	63,468.46	11,500	11.50	30,000	8	1,028
KYA-CY-K2	1,024.39	55,100.00	11,500	11.50	30,000	11	893
SEN-CY-K1	797.94	20,503.28	4,600	4.60	20,000	8	332
KAW-CY-K1	2,585.27	18,127.62	4,600	4.60	23,000	27	294
SEN-CY-K3	3,663.80	29,619.88	6,900	6.90	35,000	38	480
SEN-CY-K4	586.29	24,874.05	6,900	6.90	35,000	6	403
KKI-CY-K1	1,480.93	18,542.64	5,750	5.75	15,000	15	300
NAF-CY-K1	3,154.93	26,268.34	4,600	4.60	10,000	33	426
MPM-CY-K1	2,268.25	22,339.58	5,750	5.75	30,000	23	362
KLO-CY-K4	1,634.98	16,233.79	5,750	5.75	13,000	17	263
NNG-CY-K2	2,355.40	26,439.83	4,600	4.60	16,000	24	428
SEN-CY-K5	273.08	10,425.98	4,600	4.60	21,000	3	169
MMM-CY-K1	1,075.81	47,036.37	9,200	9.20	23,000	11	762
SEN-CY-K6	2,560.14	39,331.08	4,600	4.60	21,000	26	637
SEN-CY-K7	969.21	21,410.55	4,600	4.60	20,000	10	347
SEN-CY-K8	2,064.53	27,153.65	4,600	4.60	18,000	21	440
SEM-CY-K1	679.36	19,727.12	6,900	6.90	32,000	7	320
MKI-CY-K1	1,626.42	21,775.89	2,300	2.30	6,500	17	353
MKA-CY-K1	2,360.71	55,700.00	5,750	5.75	25,000	24	902
NMK-CY-K1	505.54	11,161.61	4,600	4.60	16,000	5	181
NAM-CY-K6	1,874.59	36,277.73	6,900	6.90	20,000	19	588
ABU-CY-K1	2,246.50	27,756.68	3,450	3.45	7,000	23	450
SEN-CY-K9	624.29	28,224.43	6,900	6.90	30,000	6	457
BUJ-CY-K1	669.60	19,302.23	4,600.00	4.60	12,000	6.90	312.70

Table 8.4: Sample Kiln Emission Data - Kiln MKA-CY-K1 (Source; Primary Data)

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	7:52:00 PM	1	60	72.58	16.67	0	2942.39	0	11.42	-51.87	134.66	4.09	11.42	82.7	323.91
MKA-CY-K1	wood	ppm	12/5/2025	7:52:00 PM	1	60	72.68	16.67	0	2942.39	0	11.42	-51.87	134.66	4.09	11.42	82.7	323.91
MKA-CY-K1	wood	ppm	12/5/2025	7:53:00 PM	1	60	72.68	16.34	0	2294.82	0	15.77	-51.56	134.72	4.4	15.77	84.09	301.42
MKA-CY-K1	wood	ppm	12/5/2025	7:53:00 PM	1	60	72.14	16.34	0	2294.82	0	15.77	-51.56	134.72	4.4	15.77	84.09	301.42
MKA-CY-K1	wood	ppm	12/5/2025	7:54:00 PM	1	60	72.14	16.54	0	2437.78	0	12.78	-52.24	134.81	4.21	12.78	80.75	306.36
MKA-CY-K1	wood	ppm	12/5/2025	7:54:00 PM	1	60	72.05	16.54	0	2437.78	0	12.78	-52.24	134.81	4.21	12.78	80.75	306.36
MKA-CY-K1	wood	ppm	12/5/2025	7:55:00 PM	1	60	72.05	16.12	0	2416.68	0	15.53	-50.71	136.09	4.61	15.53	71.52	261.34
MKA-CY-K1	wood	ppm	12/5/2025	7:55:00 PM	1	60	72.23	16.12	0	2416.68	0	15.53	-50.71	136.09	4.61	15.53	71.52	261.34
MKA-CY-K1	wood	ppm	12/5/2025	7:56:00 PM	1	60	72.19	15.58	0	2755.01	0	14.66	-51.26	136.53	5.13	14.66	33.05	221.18
MKA-CY-K1	wood	ppm	12/5/2025	7:57:00 PM	1	60	72.19	16.17	0	3115.73	0	11.77	-52.22	134.83	4.56	11.77	27.25	256.34
MKA-CY-K1	wood	ppm	12/5/2025	7:57:00 PM	1	60	71.98	16.17	0	3115.73	0	11.77	-52.22	134.83	4.56	11.77	27.25	256.34
MKA-CY-K1	wood	ppm	12/5/2025	7:58:00 PM	1	60	71.6	16.44	0	3821.94	0	12.35	-52.25	134.87	4.3	12.35	39	275.8
MKA-CY-K1	wood	ppm	12/5/2025	7:59:00 PM	1	60	71.16	16.13	0	4000	0	12.67	-52.21	134.68	4.6	12.67	100	253.74
MKA-CY-K1	wood	ppm	12/5/2025	7:59:00 PM	1	60	71.16	16.13	0	4000	0	12.67	-52.21	134.68	4.6	12.67	100	253.74
MKA-CY-K1	wood	ppm	12/5/2025	8:00:00 PM	1	60	70.98	16.05	0	4000	0	11.55	-52.25	135.65	4.67	11.55	100	248.56

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:00:00 PM	1	60	70.98	16.05	0	4000	0	11.55	-52.25	135.65	4.67	11.55	100	248.56
MKA-CY-K1	wood	ppm	12/5/2025	8:01:00 PM	1	60	70.7	15.76	0	4000	0	11.99	-52.25	135.73	4.95	11.99	100	230.74
MKA-CY-K1	wood	ppm	12/5/2025	8:01:00 PM	1	60	70.7	15.76	0	4000	0	11.99	-52.25	135.73	4.95	11.99	100	230.74
MKA-CY-K1	wood	ppm	12/5/2025	8:02:00 PM	1	60	70.7	15.59	0	4000	0	12.15	-52.25	138.53	5.11	12.15	100	221.44
MKA-CY-K1	wood	ppm	12/5/2025	8:02:00 PM	1	60	70.7	15.59	0	4000	0	12.15	-52.25	138.53	5.11	12.15	100	221.44
MKA-CY-K1	wood	ppm	12/5/2025	8:03:00 PM	1	60	71.06	15.01	0	3643.38	0	15.34	-52.25	137.53	5.67	15.34	100	192.74
MKA-CY-K1	wood	ppm	12/5/2025	8:03:00 PM	1	60	71.06	15.01	0	3643.38	0	15.34	-52.25	137.53	5.67	15.34	100	192.74
MKA-CY-K1	wood	ppm	12/5/2025	8:04:00 PM	1	60	71.6	14.97	0	2930.31	0	15.54	-52.2	138.83	5.71	15.54	100	190.88
MKA-CY-K1	wood	ppm	12/5/2025	8:04:00 PM	1	60	71.6	14.97	0	2930.31	0	15.54	-52.2	138.83	5.71	15.54	100	190.88
MKA-CY-K1	wood	ppm	12/5/2025	8:05:00 PM	1	60	71.78	15.22	0	2595.05	0	14.11	-52.25	138.28	5.47	14.11	100	202.35
MKA-CY-K1	wood	ppm	12/5/2025	8:05:00 PM	1	60	71.78	15.22	0	2595.05	0	14.11	-52.25	138.28	5.47	14.11	100	202.35
MKA-CY-K1	wood	ppm	12/5/2025	8:06:00 PM	1	60	71.95	15.23	0	2295.44	0	13.62	-52.25	138	5.46	13.62	60.37	206.43
MKA-CY-K1	wood	ppm	12/5/2025	8:07:00 PM	1	60	71.96	15.43	0	2374.72	0	14.43	-52.25	137.91	5.27	14.43	78.83	224.84
MKA-CY-K1	wood	ppm	12/5/2025	8:08:00 PM	1	60	71.96	15.59	0	2442.74	0	13.7	-52.24	137	5.12	13.7	61.74	224.9
MKA-CY-K1	wood	ppm	12/5/2025	8:09:00 PM	1	60	72.14	15.29	0	2048.52	0	15.13	-52.25	137.43	5.41	15.13	63.55	209.87
MKA-CY-K1	wood	ppm	12/5/2025	8:10:00 PM	1	60	72.14	15.07	0	1612.81	0	15.39	-51.74	138.42	5.61	15.39	34.59	197.06

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:10:00 PM	1	60	72.05	15.07	0	1612.81	0	15.39	-51.74	138.42	5.61	15.39	34.59	197.06
MKA-CY-K1	wood	ppm	12/5/2025	8:11:00 PM	1	60	72.05	14.72	0	1528.44	0	17.63	-52.23	138.93	5.95	17.63	34.28	181.97
MKA-CY-K1	wood	ppm	12/5/2025	8:11:00 PM	1	60	72.05	14.72	0	1528.44	0	17.63	-52.23	138.93	5.95	17.63	34.28	181.97
MKA-CY-K1	wood	ppm	12/5/2025	8:12:00 PM	1	60	72.05	14.46	0	1558.21	0	16.87	-52.25	139.6	6.2	16.87	28.58	171.38
MKA-CY-K1	wood	ppm	12/5/2025	8:12:00 PM	1	60	72.14	14.46	0	1558.21	0	16.87	-52.25	139.6	6.2	16.87	28.58	171.38
MKA-CY-K1	wood	ppm	12/5/2025	8:13:00 PM	1	60	72.41	14.52	0	1500.65	0	15.37	-52.25	141.03	6.14	15.37	0	172.69
MKA-CY-K1	wood	ppm	12/5/2025	8:13:00 PM	1	60	72.41	14.52	0	1500.65	0	15.37	-52.25	141.03	6.14	15.37	0	172.69
MKA-CY-K1	wood	ppm	12/5/2025	8:14:00 PM	1	60	72.05	14.57	0	1494.3	0	16.67	-52.25	141.5	6.09	16.67	100	174.69
MKA-CY-K1	wood	ppm	12/5/2025	8:14:00 PM	1	60	72.05	14.57	0	1494.3	0	16.67	-52.25	141.5	6.09	16.67	100	174.69
MKA-CY-K1	wood	ppm	12/5/2025	8:15:00 PM	1	60	71.69	14.66	0	1542.63	0	14.17	-52.25	140.6	6.01	14.17	100	178.02
MKA-CY-K1	wood	ppm	12/5/2025	8:15:00 PM	1	60	71.69	14.66	0	1542.63	0	14.17	-52.25	140.6	6.01	14.17	100	178.02
MKA-CY-K1	wood	ppm	12/5/2025	8:16:00 PM	1	60	71.2	15.08	0	1620.38	0	14.94	-52.25	139.71	5.6	14.94	100	196.09
MKA-CY-K1	wood	ppm	12/5/2025	8:16:00 PM	1	60	71.2	15.08	0	1620.38	0	14.94	-52.25	139.71	5.6	14.94	100	196.09
MKA-CY-K1	wood	ppm	12/5/2025	8:17:00 PM	1	60	71.13	15.57	0	1892.8	0	14.01	-52.25	140.93	5.13	14.01	100	220.35
MKA-CY-K1	wood	ppm	12/5/2025	8:17:00 PM	1	60	71.13	15.57	0	1892.8	0	14.01	-52.25	140.93	5.13	14.01	100	220.35
MKA-CY-K1	wood	ppm	12/5/2025	8:18:00 PM	1	60	71.64	14.96	0	1897.29	0	14.67	-52.25	140.79	5.72	14.67	100	190.47

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:18:00 PM	1	60	71.64	14.96	0	1897.29	0	14.67	-52.25	140.79	5.72	14.67	100	190.47
MKA-CY-K1	wood	ppm	12/5/2025	8:19:00 PM	1	60	71.64	15.1	0	1733.99	0	15.82	-52.25	140.17	5.59	15.82	100	196.79
MKA-CY-K1	wood	ppm	12/5/2025	8:19:00 PM	1	60	71.88	15.1	0	1733.99	0	15.82	-52.25	140.17	5.59	15.82	100	196.79
MKA-CY-K1	wood	ppm	12/5/2025	8:20:00 PM	1	60	71.88	15.94	0	1445.58	0	13.69	-52.25	140.25	4.78	13.69	100	241.43
MKA-CY-K1	wood	ppm	12/5/2025	8:20:00 PM	1	60	71.7	15.94	0	1445.58	0	13.69	-52.25	140.25	4.78	13.69	100	241.43
MKA-CY-K1	wood	ppm	12/5/2025	8:21:00 PM	1	60	71.7	15.14	0	1857.4	0	14.07	-52.25	141.09	5.55	14.07	100	198.75
MKA-CY-K1	wood	ppm	12/5/2025	8:21:00 PM	1	60	71.78	15.14	0	1857.4	0	14.07	-52.25	141.09	5.55	14.07	100	198.75
MKA-CY-K1	wood	ppm	12/5/2025	8:22:00 PM	1	60	71.6	14.8	0	1984.26	0	16.33	-52.25	141.18	5.87	16.33	71.53	189.76
MKA-CY-K1	wood	ppm	12/5/2025	8:22:00 PM	1	60	71.6	14.8	0	1984.26	0	16.33	-52.25	141.18	5.87	16.33	71.53	189.76
MKA-CY-K1	wood	ppm	12/5/2025	8:23:00 PM	1	60	71.6	14.82	0	2156.96	0	14.94	-52.25	141.89	5.85	14.94	0	184.62
MKA-CY-K1	wood	ppm	12/5/2025	8:23:00 PM	1	60	71.6	14.82	0	2156.96	0	14.94	-52.25	141.89	5.85	14.94	0	184.62
MKA-CY-K1	wood	ppm	12/5/2025	8:24:00 PM	1	60	71.6	14.56	0	1982.92	0	13.74	-51.74	142.19	6.1	13.74	51.53	176.3
MKA-CY-K1	wood	ppm	12/5/2025	8:24:00 PM	1	60	72.18	14.56	0	1982.92	0	13.74	-51.74	142.19	6.1	13.74	51.53	176.3
MKA-CY-K1	wood	ppm	12/5/2025	8:25:00 PM	1	60	72.18	14.78	0	1753.01	0	14.57	-52.23	142.32	5.89	14.57	0	183.03
MKA-CY-K1	wood	ppm	12/5/2025	8:25:00 PM	1	60	73.12	14.78	0	1753.01	0	14.57	-52.23	142.32	5.89	14.57	0	183.03
MKA-CY-K1	wood	ppm	12/5/2025	8:26:00 PM	1	60	73.12	15.05	0	1681.68	0	14.54	-52.25	142.48	5.63	14.54	100	194.66

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:26:00 PM	1	60	73.41	15.05	0	1681.68	0	14.54	-52.25	142.48	5.63	14.54	100	194.66
MKA-CY-K1	wood	ppm	12/5/2025	8:27:00 PM	1	60	73.41	14.15	0	2108	0	17.17	-51.96	142.75	6.5	17.17	37.82	160.3
MKA-CY-K1	wood	ppm	12/5/2025	8:27:00 PM	1	60	73.69	14.15	0	2108	0	17.17	-51.96	142.75	6.5	17.17	37.82	160.3
MKA-CY-K1	wood	ppm	12/5/2025	8:28:00 PM	1	60	73.69	14.02	0	2636.64	0	15.56	-52.25	143	6.61	15.56	7.84	155.17
MKA-CY-K1	wood	ppm	12/5/2025	8:28:00 PM	1	60	73.94	14.02	0	2636.64	0	15.56	-52.25	143	6.61	15.56	7.84	155.17
MKA-CY-K1	wood	ppm	12/5/2025	8:29:00 PM	1	60	73.94	14.19	0	2428.01	0	15.77	-51.99	143.53	6.45	15.77	1.02	161
MKA-CY-K1	wood	ppm	12/5/2025	8:29:00 PM	1	60	74.03	14.19	0	2428.01	0	15.77	-51.99	143.53	6.45	15.77	1.02	161
MKA-CY-K1	wood	ppm	12/5/2025	8:30:00 PM	1	60	74.03	14.26	0	2274.57	0	15.3	-52.2	143.65	6.38	15.3	0	163.44
MKA-CY-K1	wood	ppm	12/5/2025	8:30:00 PM	1	60	74.12	14.26	0	2274.57	0	15.3	-52.2	143.65	6.38	15.3	0	163.44
MKA-CY-K1	wood	ppm	12/5/2025	8:31:00 PM	1	60	74.12	14.32	0	2217.91	0	15.21	-52.24	143.28	6.33	15.21	0	165.3
MKA-CY-K1	wood	ppm	12/5/2025	8:31:00 PM	1	60	73.76	14.32	0	2217.91	0	15.21	-52.24	143.28	6.33	15.21	0	165.3
MKA-CY-K1	wood	ppm	12/5/2025	8:32:00 PM	1	60	73.76	14.27	0	1916.47	0	14.78	-51.74	142.52	6.37	14.78	35.65	164.77
MKA-CY-K1	wood	ppm	12/5/2025	8:32:00 PM	1	60	73.67	14.27	0	1916.47	0	14.78	-51.74	142.52	6.37	14.78	35.65	164.77
MKA-CY-K1	wood	ppm	12/5/2025	8:33:00 PM	1	60	73.67	14.37	0	1750.42	0	14.83	-52.25	141.67	6.28	14.83	19.63	167.88
MKA-CY-K1	wood	ppm	12/5/2025	8:33:00 PM	1	60	73.66	14.37	0	1750.42	0	14.83	-52.25	141.67	6.28	14.83	19.63	167.88
MKA-CY-K1	wood	ppm	12/5/2025	8:34:00 PM	1	60	73.58	14.9	0	1433.01	0	13.54	-52.25	141.66	5.77	13.54	0	188.2

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:35:00 PM	1	60	73.76	14.96	0	1277.14	0	13.65	-52.25	140.82	5.72	13.65	0	190.69
MKA-CY-K1	wood	ppm	12/5/2025	8:35:00 PM	1	60	73.76	14.96	0	1277.14	0	13.65	-52.25	140.82	5.72	13.65	0	190.69
MKA-CY-K1	wood	ppm	12/5/2025	8:36:00 PM	1	60	73.76	14.71	0	1280.55	0	15.11	-52.25	141.55	5.95	15.11	100	180.3
MKA-CY-K1	wood	ppm	12/5/2025	8:36:00 PM	1	60	74.3	14.71	0	1280.55	0	15.11	-52.25	141.55	5.95	15.11	100	180.3
MKA-CY-K1	wood	ppm	12/5/2025	8:37:00 PM	1	60	74.31	14.48	0	1931.52	0	11.95	-52.25	142.7	6.18	11.95	100	171.29
MKA-CY-K1	wood	ppm	12/5/2025	8:37:00 PM	1	60	74.31	14.48	0	1931.52	0	11.95	-52.25	142.7	6.18	11.95	100	171.29
MKA-CY-K1	wood	ppm	12/5/2025	8:38:00 PM	1	60	73.78	14.01	0	3428.12	0	14.17	-52.25	144.02	6.63	14.17	100	154.7
MKA-CY-K1	wood	ppm	12/5/2025	8:38:00 PM	1	60	73.78	14.01	0	3428.12	0	14.17	-52.25	144.02	6.63	14.17	100	154.7
MKA-CY-K1	wood	ppm	12/5/2025	8:39:00 PM	1	60	73.94	14.03	0	3339.18	0	14.61	-52.25	145.21	6.61	14.61	100	155.27
MKA-CY-K1	wood	ppm	12/5/2025	8:39:00 PM	1	60	73.94	14.03	0	3339.18	0	14.61	-52.25	145.21	6.61	14.61	100	155.27
MKA-CY-K1	wood	ppm	12/5/2025	8:40:00 PM	1	60	73.45	14.45	0	2984.19	0	12.42	-52.25	143.88	6.21	12.42	100	169.92
MKA-CY-K1	wood	ppm	12/5/2025	8:40:00 PM	1	60	73.45	14.45	0	2984.19	0	12.42	-52.25	143.88	6.21	12.42	100	169.92
MKA-CY-K1	wood	ppm	12/5/2025	8:41:00 PM	1	60	73.45	14.43	0	3106.23	0	13.74	-52.49	143.61	6.23	13.74	100	169.31
MKA-CY-K1	wood	ppm	12/5/2025	8:41:00 PM	1	60	73.22	14.43	0	3106.23	0	13.74	-52.49	143.61	6.23	13.74	100	169.31
MKA-CY-K1	wood	ppm	12/5/2025	8:42:00 PM	1	60	73.48	14.19	0	3598.6	0	13.32	-52.25	145.64	6.45	13.32	27.61	160.91
MKA-CY-K1	wood	ppm	12/5/2025	8:42:00 PM	1	60	73.48	14.19	0	3598.6	0	13.32	-52.25	145.64	6.45	13.32	27.61	160.91

MKA-CY-K1																		
Kiln Code	Fuel	Engineering Unit	Date	Time	Number of Samples	Sample Time	Ambient Air Temperature TA	Oxygen O2	HC/LEL	CO/SO2	Nitrogen Dioxide NO2	Nitric Oxide NO	Draft p	Flue-Gas Temperature	Carbon Dioxide CO2	Losses qA	Excess Air LAMBDA	NOx (calc.)
MKA-CY-K1	wood	ppm	12/5/2025	8:43:00 PM	1	60	73.48	13.87	0	3723.98	0	12.75	-52.25	145.8	6.76	12.75	100	150.26
MKA-CY-K1	wood	ppm	12/5/2025	8:43:00 PM	1	60	73.85	13.87	0	3723.98	0	12.75	-52.25	145.8	6.76	12.75	100	150.26
MKA-CY-K1	wood	ppm	12/5/2025	8:44:00 PM	1	60	73.85	17.06	0	1098.46	0	7.94	-52.75	146.16	3.71	7.94	100	329.11
MKA-CY-K1	wood	ppm	12/5/2025	8:44:00 PM	1	60	73.76	17.06	0	1098.46	0	7.94	-52.75	146.16	3.71	7.94	100	329.11
MKA-CY-K1	wood	ppm	12/5/2025	8:45:00 PM	1	60	73.76	15.73	0	1830.08	0	9.38	-52.26	145.63	4.98	9.38	0	229.05
MKA-CY-K1	wood	ppm	12/5/2025	8:45:00 PM	1	60	72.95	15.73	0	1830.08	0	9.38	-52.26	145.63	4.98	9.38	0	229.05
MKA-CY-K1	wood	ppm	12/5/2025	8:46:00 PM	1	60	72.95	15.57	0	2090.22	0	11.49	-52.18	146.65	5.14	11.49	0	219.92
MKA-CY-K1	wood	ppm	12/5/2025	8:46:00 PM	1	60	73.13	15.57	0	2090.22	0	11.49	-52.18	146.65	5.14	11.49	0	219.92
MKA-CY-K1	wood	ppm	12/5/2025	8:49:00 PM	1	60	73.22	15.9	0	2690.73	0	9.54	-52.75	147.59	4.83	9.54	100	238.61
MKA-CY-K1	wood	ppm	12/5/2025	8:49:00 PM	1	60	73.51	15.9	0	2690.73	0	9.54	-52.75	147.59	4.83	9.54	100	238.61
MKA-CY-K1	wood	ppm	12/5/2025	8:50:00 PM	1	60	73.51	13.57	0	4000	0	13.03	-52.25	149.14	7.04	13.03	100	141.33
MKA-CY-K1	wood	ppm	12/5/2025	8:50:00 PM	1	60	73.93	13.57	0	4000	0	13.03	-52.25	149.14	7.04	13.03	100	141.33
MKA-CY-K1	wood	ppm	12/5/2025	8:51:00 PM	1	60	73.93	13.46	0	4000	0	11.82	-52.25	149.29	7.15	11.82	100	138.06
MKA-CY-K1	wood	ppm	12/5/2025	8:51:00 PM	1	60	74.39	13.46	0	4000	0	11.82	-52.25	149.29	7.15	11.82	100	138.06
MKA-CY-K1	wood	ppm	12/5/2025	8:52:00 PM	1	60	74.39	13.69	0	4000	0	12.82	-52.28	149.68	6.93	12.82	100	144.76