



The thermal and emission performance of a novel wood-burning cookstove

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Chemical Engineering* at the North-West University

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DECLARATION

I, Shimoné Bridges, hereby declare that the dissertation entitled: “The Thermal and Emissions Performance of a Novel Wood-burning Cookstove”, submitted in fulfilment of the requirements for the Master in Chemical Engineering degree, is my own work except where acknowledged in the text, and it has been language edited as required. Language and grammar editing was conducted with the help of AI technology, specifically Grammarly and Writefull. This dissertation has not been submitted to any other tertiary institution in whole or in part. I understand that the copies handed in for examination are the property of the North-West University.

Signed at Potchefstroom on the ____26th____ day of November 2024.



S. Bridges (31671330)

CONFERENCE PROCEEDINGS

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DEDICATION

This work is dedicated to my grandfather, Dennis Bown, whose love, guidance, and wisdom shaped so much of who I am. Though you are no longer here to see me complete this journey, your memory continues to inspire me every day. I wish you could be here to witness this moment, but I know you would be proud of me.

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ABSTRACT

Indoor air pollution from burning solid fuels on makeshift stoves and open fires in low-income households is a significant health concern, causing respiratory illnesses, heart disease, and cancer. According to the World Health Organisation (WHO), this leads to 3.2 million premature deaths worldwide each year. In South Africa, poor socio-economic conditions and limited access to electricity drive the dependence on solid fuels, making exploring cleaner and more efficient cooking technologies essential.

This study evaluates a novel wood-burning stove, the Flamingo™ stove, designed to reduce emissions and increase fuel efficiency. A novel feature of the stove design is an integrated oven and a deflecting plate (or flap) that allows two configurations: oven in use and oven not in use. The performance of the stove was evaluated using four common South African wood species: Sickie Bush (*Dichrostachys cinerea*), Mopane (*Colophospermum mopane*), Leadwood (*Combretum imberbe*), and Black Wattle (*Acacia mearnsii*). Initially obtained as firewood logs, the wood species were cut into 15 x 15 x 250 mm cuttings to fuel the stove, which was initially designed to utilise twigs. The Heterogeneous Testing Protocol (HTP) was employed to replicate real-life cooking conditions, with key performance indicators determined using thermocouples, gas analysers, and particulate matter monitors.

Sickie Bush showed the fastest burn rate and the highest firepower, 4.1 ± 0.8 kW, while Leadwood showed the lowest firepower output at 2.8 ± 0.3 kW. Temperature trends varied by species; Sickie Bush exhibited the highest fuel bed temperature, unlike Leadwood, which showed the lowest burn rate and fuel bed temperature. The highest effective thermal efficiency was seen from Black Wattle, showing a low power phase efficiency of $26.2 \pm 9.3\%$.

The four local wood species showed emission factors comparable to those in previously reported studies. (Bentson *et al.*, 2022; Deng *et al.*, 2022; Huangfu *et al.*, 2014; Makonese & Bradnum, 2018). NO_x and SO₂ emission factors shown by the Flamingo™ stove ranged between 0.08–0.13 g/MJ and 0.04–0.13 g/MJ, respectively. The highest CO₂ emission factor was from Leadwood, 103 ± 4.0 g/MJ; the remaining three species showed lower 91–95 g/MJ values. PM and CO emission factors between 0.06–0.11 g/MJ and 3.1–4.1 g/MJ were observed, comparable to other cookstove models. The faster-burning species showed increased CO/CO₂ ratios due to higher degrees of incomplete combustion.

The four species showed good emission performance (Tiers 3-4) but performed poorly on thermal efficiency (Tiers 1-2). Black Wattle showed the best overall performance—Tier 4 for CO emissions, Tier 4 for PM emissions and Tier 2 for thermal efficiency.

The use of the oven had a minor influence on the stove's thermal efficiency, showing an increase of up to 5% when the oven was in use. The effective thermal efficiency of the species over the separate phases ranged between 11.7–29.9% when the oven was in use. As slight differences show, the oven did not significantly influence the emission factors, possibly due to experimental uncertainties. Tier performance changed slightly when the oven was used, with an increase from Tier 1 to Tier 2 for thermal efficiency by both Sickie Bush and Mopane.

The study highlighted that different wood species significantly impact stove performance, making the choice of wood dependent on the user's specific needs.

Key terms

clean cookstove, improved cookstove, clean cooking, wood combustion, emission performance, thermal efficiency

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LIST OF ABBREVIATIONS

List of abbreviations	
ASTM	American Society for Testing and Materials
CFD	Computational Fluid Dynamics
COPD	Chronic obstructive pulmonary disease
CV	Calorific Value
EF	Emission factor
HAP	Household air pollution
HELE	High efficiency, low emission
HEPA	High-efficiency particulate air (filter)
HTP	Heterogeneous Testing Protocol
ICS	Improved cookstove
ISO	International Organization for Standardization
LHV	Lower heating value
NWU	North-West University
PM	Particulate matter
SFC	Specific fuel consumption
TCS	Traditional cookstove
TLUD	Top-lit Updraft
TSP	Total suspended particles
VOC	Volatile organic components
WBT	Water boiling test
WHO	World Health Organisation

CHAPTER 1 INTRODUCTION

1.1 Background and motivation

Air pollution can be partly attributed to diverse human activities, including industrial processes, transport, energy generation, the agricultural sector and, specific to this study, household energy generation (Manisalidis *et al.*, 2020; World Health Organization, 2022b). Air pollution poses a significant global challenge due to its impact on the environment and human health. Among these activities, the most important contributing factor to the severity of air pollution and climate change is the combustion of fossil fuels, such as coal, natural gas, and petroleum products (Manisalidis *et al.*, 2020). The domestic use of solid fuels can also significantly contribute to both indoor and ambient air pollution (Chafe *et al.*, 2014). The use of domestic fuels contributes to the decline in local air quality in specific communities.

The use of makeshift stoves and open fires to burn solid fuels in lower-income households generates and exposes users to pollutants that harm their health (World Health Organization, 2022a). According to the World Health Organisation (WHO), indoor pollutants emitted from burning solid fuels result in 3.2 million premature deaths annually worldwide (World Health Organization, 2022a). Burning of wood results in the release of pollutants such as CO, particulate matter (PM_{2.5} and PM₁₀) and, to a lesser extent, SO_x and NO_x (Wood Energy, 2019). The indoor burning of solid fuels leads to higher indoor concentrations of emissions than in the ambient air, which results in a higher exposure rate (Vicente *et al.*, 2020). Using solid fuels indoors is increasingly related to various health risks, including heart disease, stroke, respiratory illnesses, and cancer (Balmes, 2019; Lim *et al.*, 2012; Pathak *et al.*, 2020).

Cooking is essential in ensuring the health and well-being of humans. Cooking eliminates any foodborne bacteria, reduces the risk of contamination and serves as a water purification method in areas where clean water is not readily available. Cooking also enhances the nutritional value of certain foods. In South Africa, costly electricity access and poor economic conditions are primary factors for using solid fuels, makeshift stoves, and open fires in lower-income households for cooking and heating purposes. In 2020 in South Africa, only 84.4% of households had access to electricity, and 85% in 2019 (World Bank, 2020b). According to Statistics SA (2016b), 64% of Limpopo households use electricity for cooking. Electricity is used in 50% of households for space heating and 64% of households for water heating (Statistics SA, 2016b). Although many households have access to electricity, financial constraints lead to the use of cheaper energy sources, such as biomass or paraffin, for cooking and heating. According to a survey conducted in the Dikgale subdistrict in Limpopo, the first alternative used when out of electricity is wood (Sustainable Energy Africa, 2016).

One solution to combat indoor air pollution is the implementation of improved cookstoves. Improved cookstoves aim to reduce fuelwood consumption, produce lower emissions and provide higher thermal efficiency than traditional solid-fuel cookstoves (Kulkarni *et al.*, 2022; Mekonnen, 2022). These high-efficiency, low-emission (HELE) stoves thus have both economic and health benefits for users. Only 66% of the rural South African population have access to clean and safe cooking technology alternatives, such as improved cookstoves (World Bank, 2020a), but 69% of South African households consulted in a small survey preferred cooking with an improved cookstove rather than traditional stoves (Jewitt *et al.*, 2018).

Improved cookstoves can also be used as part of an emission offset strategy. Emission offsetting entails projects where companies provide funding for emission-reduction initiatives to compensate for their industrial emissions while still showing effort to reduce the emissions from said company. In the South African context, emission offset projects are regulated by the Air Quality Offsets Guideline, as included in the National Environmental Management Act of 1998 (Department of Environmental Affairs, 2016). Offset programmes should meet the offsetting principles as outlined in the guidelines (Department of Environmental Affairs, 2016), including:

- The programme should be based on improving ambient air quality in the designated area.
- Should address the ambient concentration of pollutants in the specific area.
- Should be transparent and acceptable.
- Should be sustainable.
- Should be scientifically measurable and robust.

A low-emission coal stove has been in development since 2014 at the North-West University (NWU), in conjunction with New Dawn Engineering, with various MEng studies on it (Kühn, 2015; Maass, 2023; Sumbane-Prinsloo, 2018). The performance of different fuel types, CFD modelling, and the community implementation of the coal stove have been considered (Meyer *et al.*, 2021; Sumbane-Prinsloo *et al.*, 2021). Coal is not readily available for domestic use, specifically in rural communities, and consequently, a need for wood stoves arises. A separate study of wood-fuelled stoves is motivated, as wood and coal have distinct composition and combustion properties. Improved coal stoves cannot be expected to perform well when substituting wood for coal.

A novel wood-burning cookstove, the Flamingo™™ stove, was obtained for testing. Designed by two entrepreneurs, Doubt Rusenga and Khulani Dewa, the Flamingo™ stove uses small wood pieces (twigs) to avoid cutting trees for fuelwood. This two-plate (dual hob) stove is specifically designed for cooking, not space heating. A novel design feature is an oven regulated by a deflecting plate (flap), with two orientations – the vertical position for when the oven is to be used and the horizontal position when the oven is not in use. The Flamingo™ wood-fired cookstove has not been previously evaluated at NWU or elsewhere for quantitative thermal and emissions

performance. Limited literature is available specifically for South African wood-fuelled cookstoves since past research focused primarily on coal stoves.

1.2 Problem statement

Using makeshift stoves and solid fuels indoors in lower-income homes for cooking and heating leads to indoor air pollution and poor local air quality. In South Africa, many households close to coal fields rely on coal for household energy supply. Away from active coal mining districts, such as the Limpopo Province, households rely more on wood due to its low cost and easy accessibility. However, traditional wood-burning stoves often have low thermal efficiency and poor emissions. A gap exists in the literature on improved cookstoves' emission and thermal performance when using local South African wood species.

A novel wood stove was identified as a possible intervention within these rural areas. The identified stove was designed by community entrepreneurs, which provides better insight into the community's needs. The stove design aims to improve thermal efficiency and reduce emissions when burning locally available wood species. The novelty of this stove lies within its integrated oven, a feature not commonly found in improved cookstoves.

The emission characteristics, thermal efficiency and suitability for the end-user's needs are key factors in determining its feasibility as a cleaner cooking solution. The impact of the novel feature of the stove's integrated oven on the overall emission and thermal performance will be assessed to determine the viability of roasting and baking without compromising air quality and fuel use.

1.3 Aim and objectives

This study aims to determine a novel wood-burning stove's thermal and emission performance using wood species widely available in the Limpopo province, South Africa.

To fulfil the aim of the study, the following objectives are set:

- Identify, source and characterise frequently used fuelwood species from the Limpopo province.
- Identify and commission a novel wood-fuelled stove.
- Evaluate the stove's emission and thermal performance for the selected wood species and assess how different wood species affect stove performance.
- Evaluate the stove's performance against international benchmarks and compare it with other wood-fuelled cookstoves.

1.4 Scope of the study

This study will be limited to four local wood species—three hardwood species common in the Limpopo Province of South Africa and one species widely available throughout the country. Wood is currently a widely used fuel for household energy, collected in many rural communities for no cash outlay, which implies that users will accept wood-fuelled stoves. Although alternative energy sources such as coal, LPG gas or electricity (when available) may be preferred, all require cash expenditures.

The design of the woodstove is excluded from this study. The study will focus on testing a novel stove, branded as the Flamingo™ stove, designed by two entrepreneurs. The stove has an oven activated by a deflecting plate (flap) as a heat flow regulator. The deflecting plate allows for two configurations. With the flap in the horizontal orientation, the oven is not in use, and both cooking hobs can be used at high power. The oven is heated with the flap in the vertical orientation, and the second hob can be used in a low-power, simmering mode. The influence of the use of the oven will be investigated.

Differing properties of wood species could influence a stove's performance. Determining the stove's performance using only a single species could give an incomplete depiction. Accordingly, the scope of the study includes evaluations using three commonly used species in the Limpopo province and one species widely used across South Africa, meaning four predominant wood species are tested. When used together, the compatibility between these species and a novel wood-burning stove will be considered by quantifying the species' and the stove's emission and thermal performance.

Wood fuel pieces' size (diameter) affects combustion and emission performance. To directly compare differences due to wood species, the effect of wood size was artificially constrained by sawing the fuelwood pieces to uniform size (15 mm x 15 mm x 250 mm) blocks, typical of the twig size for which the stove was designed. Performance using uniformly sized fuel pieces will differ from real-world applications. However, this strategy will reduce the masking of the variability of performance due to different species, which is the core objective of this study.

The testing method used is the Heterogeneous Testing Protocol (HTP) (Makonese, 2018; Robinson *et al.*, 2010). The test sequence consists of three power phases to simulate real-life cooking events. Instruments such as thermocouples, gas analysers, PM monitors and filters measure the stove's performance parameters.

The scope of the study, including the wood species, testing procedure and performance quantification, is summarised in Figure 1-1.

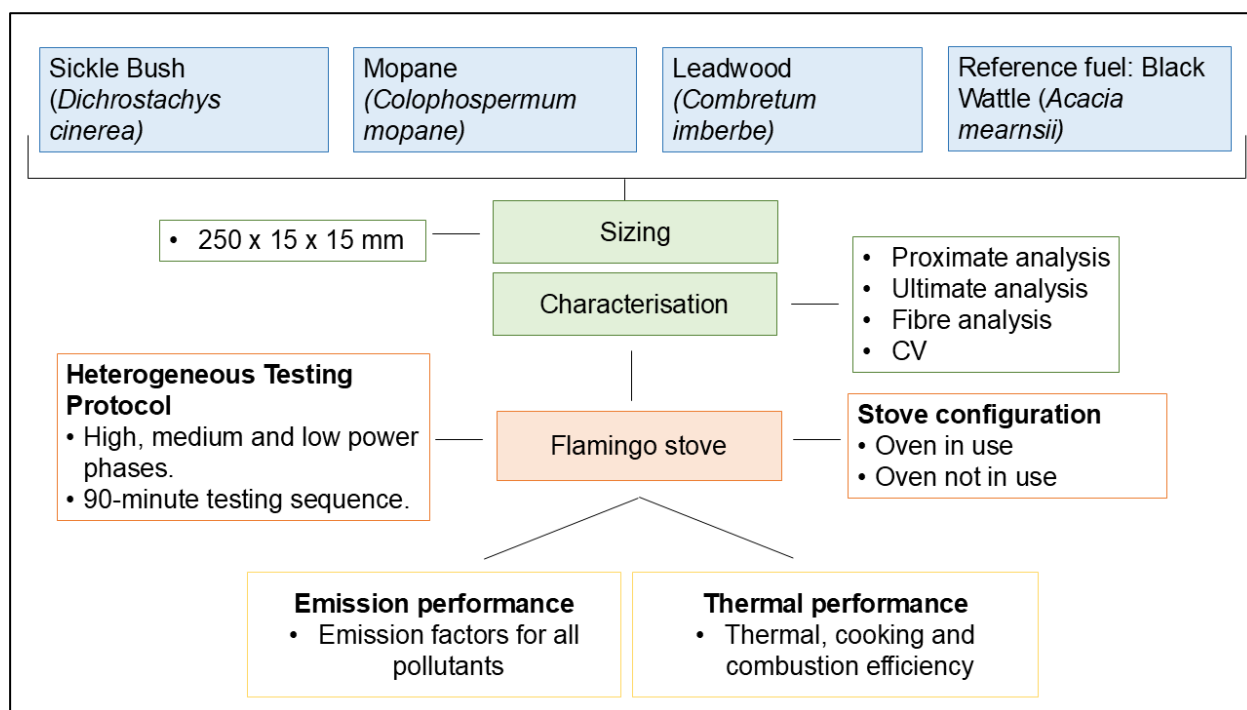


Figure 1-1: Scope of the study.

1.5 Outline

The procedures and outcomes of this study are presented as a six-chapter dissertation. The first chapter offers an introduction to the background and the aim of the study. Chapter 2, a review of the available literature, will focus on the existing literature on the various topics this study covers. The properties of wood, wood use in Limpopo, wood-burning improved cookstoves, emission factors and stove testing will be discussed. A summary of the findings will be presented. Chapter 3 will focus on the experimental methods and procedures used to reach the study's objectives, including determining the emission and thermal performance of the wood species and the Flamingo™ wood stove. The results obtained from the characterisation and cookstove experiments will be presented and discussed in Chapter 4. Finally, the conclusions and recommendations for future studies will be presented in Chapter 5.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Chapter 2 covers the literature on topics related to this research problem. The literature study provides the background information to understand the situation thoroughly and acts as a guide to a solution. Section 2.2 covers domestic energy use in low-income South African households, identifying the necessity of solid fuel as a domestic energy source. The health and environmental impacts of solid fuel are explored in Section 2.3. This section presents the magnitude of the risks associated with indoor air pollution and motivates the need for cleaner cooking technologies. Section 2.4 provides information on existing and newly improved cookstoves and their performance, highlighting the viability of improved cookstoves as a solution to indoor air pollution. Section 2.5 focuses on improved wood cookstoves, considering the wood combustion reaction. The standard testing procedure under laboratory conditions is outlined in Section 2.6. Lastly, Section 2.7 looks at previous field studies and their findings.

2.2 Energy access in low-income South African households

In 2021, approximately 770 million people worldwide were observed to live without access to electricity, and more than 2 250 million people lived without access to clean cooking methods (International Energy Agency, 2022). In 2022, some improvements have been made, but 750 million people still do not have access to electricity, while 2 000 million people lack access to improved cooking methods (International Energy Agency, 2023). Unfortunately, South African households are not exempt from these global trends.

Household electricity consumption in South Africa accounts for 26.6% of total electricity consumption in South Africa, making it one of the largest electricity consumer sectors in the country (Figure 2-1).

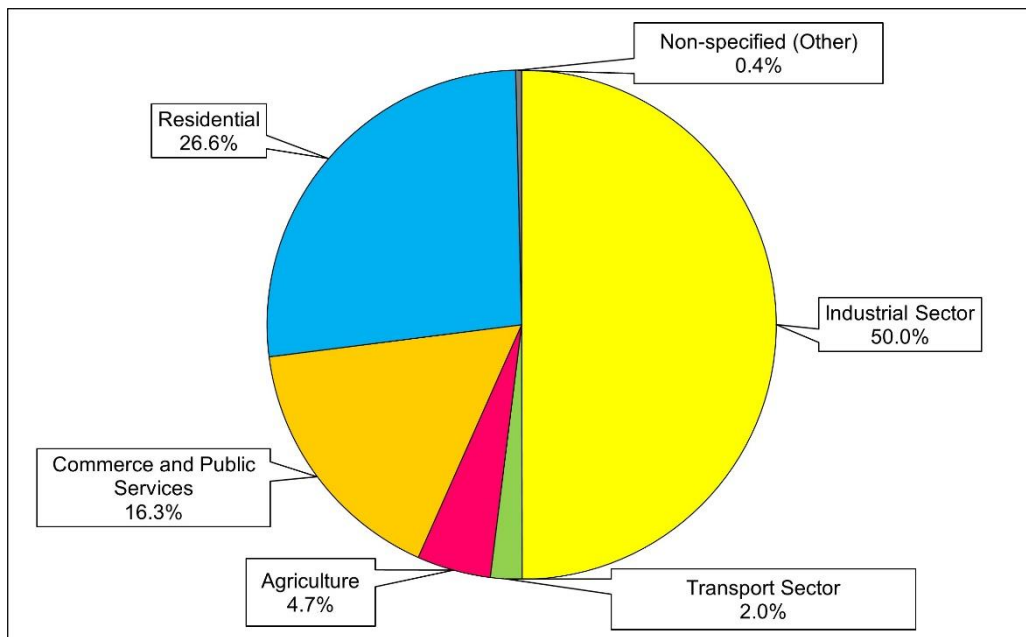


Figure 2-1: Electricity consumption by sector in South Africa in 2021. Adapted from the Department of Energy (2020).

Figure 2-2 shows the percentages of South African households that use electricity for cooking.

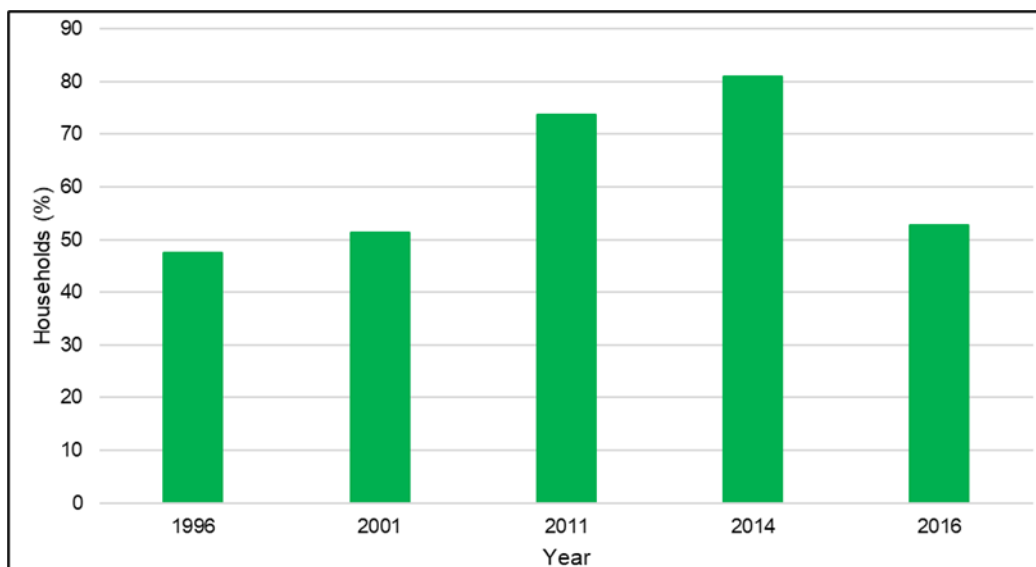


Figure 2-2: Households (%) using electricity for cooking. Adapted from Statistics SA (2016a).

Although access to electricity in South African households has increased, only 64.9% of households with access to electricity use it for cooking (Statistics SA, 2023). When looking at the main metropolitan areas, such as Johannesburg, Pretoria, and Cape Town, only 59, 63, and 64% have access to electricity for cooking, respectively (Statistics SA, 2023). This shows that alternative fuels for cooking, including gas, paraffin, coal, and wood, are needed. In South Africa, increased load-shedding negatively impacts electricity access, driving people toward using alternative energy sources, including solid fuels.

Focussing on the Limpopo province of South Africa, in 2016, 64% of households had access to electricity for cooking purposes (Statistics SA, 2016b). The most recent Census (completed in 2022) reported a decrease in the number of households, reporting that only 49% of households had electricity access being used for cooking (Statistics SA, 2023). It is reported that 31% of households use wood for cooking purposes (Statistics SA, 2023). Only 64% and 50% of households perform space heating and water heating using electricity, respectively (Statistics SA, 2016b). Considering the poor economic conditions experienced by households and their insufficient access to electricity, there is a need to explore alternative energy sources.

After electricity, a popular source of household energy is wood. A community survey conducted in the Thulamela Local Municipality in Limpopo showed that households use fuelwood as it is always available (52% of households) and due to its affordability (38.4% of households) (Netshipise & Semanya, 2022). Lesser factors for increased fuelwood use in the area are convenience (3.0%), economic value (3.0%), ease of use (2.0%) and lastly, the taste of food when used (1.0%) (Netshipise & Semanya, 2022).

Another survey on energy use conducted in the Dikgale village in the local municipality revealed that 25.6% of households use a combination of electricity and firewood for cooking purposes, while 9.6% of households use only firewood (Sustainable Energy Africa, 2016). The survey reported that 36% of households often run out of electricity to cook, of which 64% is due to a lack of money, and 26% is due to technical failures such as load-shedding (Sustainable Energy Africa, 2016). Firewood is the first alternative for 44% of households that run out of electricity (Sustainable Energy Africa, 2016).

The above statistics show a clear need for solid fuel, specifically wood, as an energy source for cooking in the Limpopo province of South Africa. It is important to note that electricity access does not substitute for the use of solid fuels in households; it is used simply in conjunction with other fuels (Bohlmann & Inglesi-Lotz, 2018). The shift from traditional fuels to newer technologies is more gradual, and it is seen that fuel stacking (the use of traditional fuel after the implementation of modern technologies) is more likely than a complete shift (Kaputo *et al.*, 2023). Solid fuel use is the primary concern since using open fires, and traditional cookstoves pose serious health and safety risks to human health and local air quality.

2.3 Health and environmental impacts of solid fuel use

The generation of household energy from solid fuels is one of the leading causes of both local ambient and household air pollution (HAP) in low-income settlements in South Africa (Nkosi *et al.*, 2021). This is a global issue since approximately 2.4 billion people worldwide still rely on solid fuels for cooking, which contributes to an estimated 3.2 million premature deaths annually due to poor indoor air quality (World Health Organization, 2022a).

2.3.1 Health risks

The emissions from indoor combustion usually consist of a mixture of gases and particulate matter (PM), which manifest in high concentrations in the cooking area of homes (Grabow *et al.*, 2013). Indoor biomass combustion exposes household members to PM, carbon monoxide (CO), carbon dioxide (CO₂), nitrogen dioxide (NO_x), sulphur dioxide (SO₂), and volatile organic compounds (VOCs) (Apte & Salvi, 2016).

Particulate matter refers to the suspension of fine particles in the air. Particulate matter is classified as PM_{2.5} (diameter less than 2.5 µm) and PM₁₀ (diameter between 10 and 2.5 µm). The size of PM is directly correlated with an increased risk of health problems: smaller particles pose a higher risk and cause more adverse effects than larger particles (Li *et al.*, 2018). Long- and short-term exposures to PM_{2.5} are associated with an increased risk of developing heart disease, heart failure, and cerebrovascular disease while aggravating existing heart conditions (Hamanaka & Mutlu, 2018). Exposure is associated with a higher risk of heart failure and fatal and non-fatal heart attacks (Madrigano *et al.*, 2013). Exposure to PM is also associated with an increased incidence of strokes and, in some cases, cancer (World Health Organization, 2022b).

Exposure to NO₂ (and other NO_x) negatively impacts the human respiratory system and can worsen symptoms of existing respiratory diseases or cause the development of new diseases (EPA, 2023b). NO_x can penetrate throughout the respiratory tract since it is not readily soluble in water (Boningari & Smirniotis, 2016). It penetrates the lungs to cause asthma, bronchitis, and emphysema and worsens existing heart problems (Boningari & Smirniotis, 2016).

Exposure to SO₂ affects the human respiratory system. Exposure to SO₂ results in bronchitis, bronchospasm, and other respiratory irritations (Manisalidis *et al.*, 2020). Exposure makes breathing difficult, increases the risk of lung infections, and worsens existing respiratory diseases (EPA, 2023c). It is a severe irritant to the eyes, mucous membranes, and skin (Agency for Toxic Substances and Disease Registry, 2014).

Other pollutants, such as VOCs (benzene, toluene), are carcinogenic, while carbon monoxide can cause headaches, dizziness, and nausea before one loses consciousness (Manisalidis *et al.*, 2020). According to Li *et al.* (2015), the indoor use of solid fuels can lead to premature ageing of the skin of women exposed to cookstove fumes. A common disease caused by solid fuel exposure is chronic obstructive pulmonary disease (COPD). A study by Long *et al.* (2021) reported a positive link between COPD and exposure to solid fuel emissions.

Although most hazard studies on cookstoves report health risks associated with emission exposure, cookstove burns are frequently observed (Mehta *et al.*, 2023). Analysis of the WHO Global Burn Register data by Mehta *et al.* (2023) reported that approximately 25% of burn patients sustained cooking-related burns. More than 40% of cooking burns are suffered by children under

five years old (Mehta *et al.*, 2023). The safety of cookstoves should thus be considered to limit burn injuries while mitigating the health risks associated with cookstove emissions.

2.3.2 Environmental impact

Indoor and ambient pollutants have a direct effect on the environment. Some of the major concerns include acid rain, haze, ozone, global climate change, and eutrophication (Manisalidis *et al.*, 2020).

Acid rain is formed when NO_x and SO_2 pollutants react with water to produce rain containing a high concentration of sulfuric and nitric acid (Ashfaq & Sharma, 2012; Manisalidis *et al.*, 2020). Acid rain acidifies water sources, harming aquatic animals, and acidifies soil and damages plants (Ashfaq & Sharma, 2012).

Particulate matter, NO_x and SO_2 cause haze since gaseous emissions from residential or industrial processes convert to particles, thereby reducing visibility (Manisalidis *et al.*, 2020). Haze occurs when sunlight is deflected or absorbed by pollutant particles, reducing the clarity of the surroundings, as seen in Figure 2-3 (EPA, 2023e). NO_x and SO_x form aerosols by reacting with ammonia to produce ammonium nitrate and sulphate. These aerosols are both pneumotoxic and immunotoxic (Bae *et al.*, 2020). SO_2 relates to the formation of secondary PM (Jutterström *et al.*, 2021). Ozone is also formed between NO_x and VOCs, which negatively impacts human health and agricultural activities (Clappier *et al.*, 2021).



Figure 2-3: Smog, or haze, during the day. (Gindin (2014), from Unsplash.)

Global climate change is an increasing concern. Greenhouse gases that accumulate in the atmosphere interfere with the greenhouse effect, hindering the ability to keep its temperature stable (Manisalidis *et al.*, 2020). Thus, an increase in Earth's temperature has been observed over the past few decades. Evidence of this includes increasing ocean temperatures, melting

glaciers, increased sea levels, higher occurrences of extreme weather events, and ecosystem changes (EPA, 2023a). This threatens human health, contributes to forest degradation and harms the agricultural sector (Manisalidis *et al.*, 2020).

Solid fuels and cookstoves also contribute to ambient air pollution and, consequently, to the increase in greenhouse gas emissions. Coal and wood cookstoves release CO, CO₂ and other greenhouse pollutants contributing to global warming. Wood cookstoves are also contributing towards deforestation. Although cookstoves contribute to global warming, the average household user is not as concerned with it as they are with cooking for themselves. The impact of cookstoves in this regard is not part of this study's scope, focusing on user behaviour and the direct impact of cookstoves thereon.

2.4 Improved cookstoves

Improved cookstoves are considered a viable intervention for the safer use of solid fuels. The purpose of an improved cookstove is to use as little fuel as possible to provide enough energy for cooking and space heating while limiting emissions. Cookstoves are constantly being tested, optimised and improved to further the benefits within communities (Clean Cooking Alliance, 2020). The Clean Cooking Alliance is a focal point for stove research and development.

2.4.1 Types of cookstoves

Cookstoves are classified as traditional or improved (clean). Traditional cookstoves (TCS) are usually archaic designs, characterised by low fuel, thermal, and emission efficiency (Yunusa *et al.*, 2023). In traditional cookstoves, incomplete combustion is often observed due to lower temperatures in the stove, resulting in high emissions of CO, VOCs and PM (Sutar *et al.*, 2023). The simplest example of traditional cookstoves is the use of three-stone fires. Three stones (or bricks, piles of mud, etc.) are used as a stand for a pot, with a fire directly beneath it. In South Africa, another popular example is the use of braziers, or imbaulas, a stove made from a metal drum, by making holes around the sides of the drum and fixing a grate inside to serve as a fuel bed (Makonese *et al.*, 2017). The braziers are used to burn a variety of fuels, including coal, biomass, and trash (Makonese *et al.*, 2017).

Improved or clean cookstoves (ICS) are designed to have higher efficiency and lower emissions than traditional cookstoves while improving safety, lowering costs, and saving user time (Energy Catalyst, 2024; Yunusa *et al.*, 2023). A closed combustion chamber usually achieves higher efficiency in a cookstove by ensuring complete combustion, thereby increasing the heat transfer from the stove to the cooking pot and decreasing heat loss to the environment (Energy Catalyst, 2024). These are characteristics that traditional stoves and open fires lack. Cookstoves that depend on clean fuel types (Figure 2-4) are excluded from the term 'improved cookstoves', as an improved cookstove refers to a stove that efficiently burns a polluting fuel and reduces its impact

thereof (Energy Catalyst, 2024). It is essential to ensure compatibility between a cookstove and the fuel used, as cookstoves are only efficient and safe when used with the fuel they were designed for.

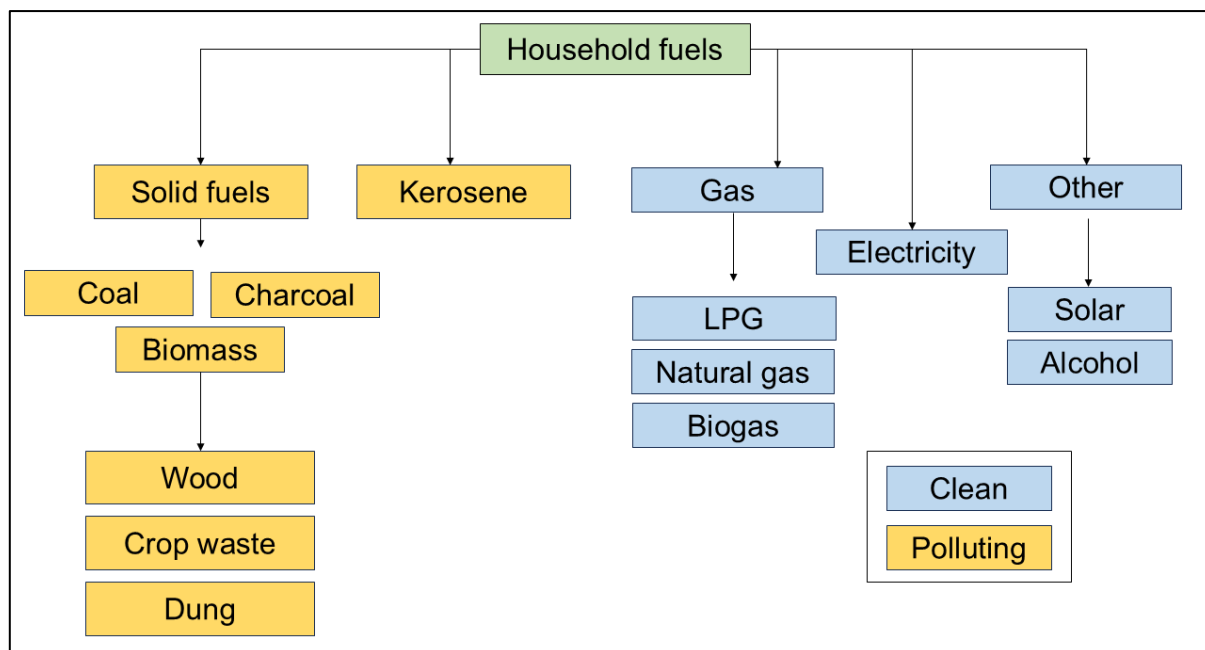


Figure 2-4: Fuel classification in cookstoves (Stoner et al., 2021).

Examples of improved cookstoves include low-emission charcoal stoves, chimney cookstoves, forced air cookstoves, Top-Lit Up-Draft (TLUD) or gasifier stoves, plancha stoves and rocket or side feed stoves (Clean Cooking Alliance, 2023).

2.4.2 Performance comparison between improved and traditional stoves

Improved cookstoves (ICS) are designed to outperform traditional cookstoves (TCS) in fuel use, emissions, and thermal efficiency. Table 2-1 shows examples of improved cookstoves that are more efficient than traditional stoves. Older improved cookstoves, such as braziers, exhibit lower thermal efficiency, showcasing progress in developing clean, efficient cookstoves. The economic benefits of an improved cookstove can be observed since the specific fuel consumption (SFC) is lower.

Table 2-1: Thermal performance of improved cookstoves and traditional cookstoves.

Performance factor	ICS	ICS	TCS	TCS
Stove type	Wood-burning stove with two secondary air inlets.	Wood-burning rocket stove.	Three stone fire burning wood.	Wood-burning brazier.
Study	Makonese and Bradnum (2018)	Mekonnen (2022)	Mekonnen (2022)	Kimemia <i>et al.</i> (2011)
Thermal efficiency (%) on hot start*	26.5 ± 3.7	32.2	13.5	15.2 ± 0.6
SFC (kg/L)**	0.02 ± 0.00	0.8	1.3	0.10 ± 0.01

*Thermal efficiency: Efficiency is based on the water boiling test, the energy absorbed by pot-plus-water on the stove.

**Specific fuel consumption (SFC): The amount of fuel (kg) needed to heat 1 L of water during a water boiling test.

The emission performance between traditional and improved cookstoves is compared in Table 2-2. It is observed that improved cookstoves have lower emissions and are safer to use. Older stoves, for example, the one tested by MacCarty *et al.* (2008), exhibit higher emissions than the newer cookstove technologies.

Table 2-2: Comparing the emissions of improved cookstoves to traditional stoves.

Performance factor	ICS	ICS	TCS	TCS
Stove type	Wood-burning double pot rocket stove.	Wood-burning rocket stove.	Three stone fire burning wood.	Wood-burning double pot stove.
Study	MacCarty <i>et al.</i> (2008)	Mekonnen (2022)	Mekonnen (2022)	MacCarty <i>et al.</i> (2008)
Highest CO conc. (ppm)	17.0	16.8	86.9	34.0
Highest PM2.5 conc. (µg/m³)	2 000	65	300 000	3 800

2.4.3 Community acceptance

Although improved cookstoves have various health, economic and environmental benefits, communities worldwide do not readily accept the implementation thereof in their homes (Brakema *et al.*, 2020).

Adoption and acceptance of improved cookstoves depend on factors such as socioeconomic conditions, age of household members, sex of the household head, education level of the household head, and family size (Mamuye *et al.*, 2018). The findings of a community study on the acceptance of cookstoves, carried out by Mamuye *et al.* (2018) in Dodda Town, Ethiopia, are summarised in Figure 2-5 and Figure 2-6. A higher level of formal education is reported to result

in a higher acceptance rate. The heads of households with formal education are more accepting of clean cookstoves, as shown by 62% of adopter households with heads of households with formal education (Figure 2-5). Observations show that households with female heads are more accepting of ICS. This is expected since women cook, especially in more traditional communities. Figure 2-6 shows male-headed households' tendency to deny the implementation of cookstoves. Female-headed households comprise 3% of non-adopter households, while 35.6% of adopter households have female heads of households.

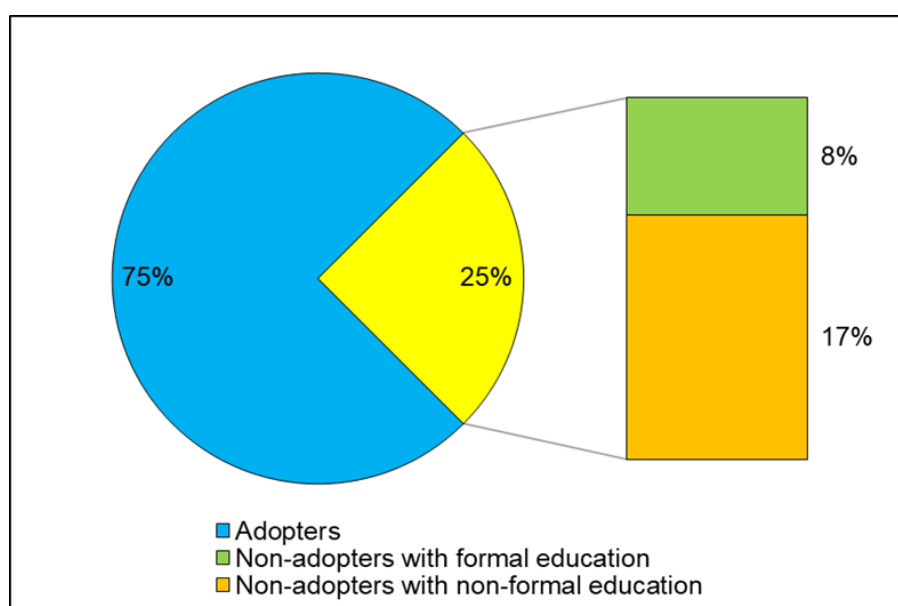


Figure 2-5: Acceptance of ICS is based on the education level of the household.

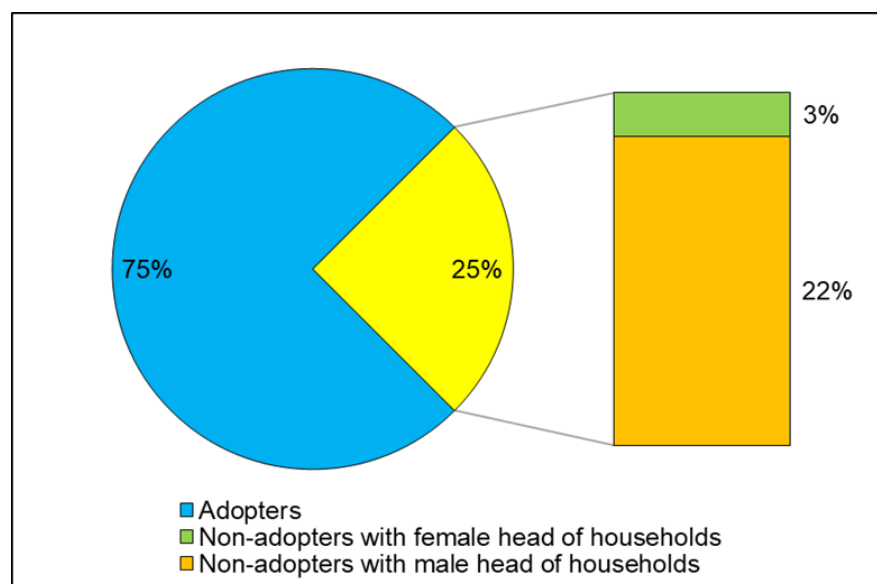


Figure 2-6: Acceptance of ICS based on the head of the household.

Various implementation strategies have been tried and tested, while only a few have proved successful. Some strategies fail due to the stove design or performance, caused by a lack of knowledge of communities and their needs (Abdelnour & Pemberton-Pigott, 2018; Brakema et

al., 2020; Soini & Coe, 2014). It is crucial to understand the user and community, their habits, and the economic conditions in which they live to provide them with a stove they can easily use. Stove programmes succeed when community preferences are considered, prioritising affordability, easy construction, ease of use, compatibility with various fuel types, and saving fuel or time for users (Barnes *et al.*, 1994; Brakema *et al.*, 2020). The success of more recent cookstove projects can be attributed to the community's involvement in the design and the inclusion of local artisans in the construction and maintenance of the stoves (Whiteman *et al.*, 2018).

Besides involving the community in the design process, other measures can be implemented by the government and non-governmental organisations to ensure higher ICS acceptance. Education and awareness programmes, subsidies and financial help to lower costs of ICS, tax incentives, and an optimised supply chain are a few examples (Kaputo *et al.*, 2023)

2.4.4 Alternative applications of cookstoves

An alternative application of improved cookstoves for the benefit of the industrial sector is emission offset programmes. Emission compensation consists of projects in which companies provide funds for emissions reduction initiatives to compensate for their industrial emissions, while still demonstrating efforts to reduce the emissions of that company (Department of Environmental Affairs, 2016). Worldwide, institutions are implementing emission reduction programmes to comply with the ambient air quality standards established by governments and the WHO. The South African Air Quality Act (Act 39 of 2004) sets out the South African standards for emission quantities. It is used along with the Air Quality Offsets Guideline, as included in the National Environmental Management Act of 1998, to regulate emission offsets. Emission offset initiatives and programmes are often implemented as part of a more extensive and comprehensive emission reduction strategy to help achieve set emission goals (Kollmuss, 2010).

2.5 Wood cookstoves

Coal stoves and low-smoke fuels have been developed and tested in South African Highveld areas, where coal is the leading domestic energy source within low-income communities (Kühn *et al.*, 2017; Phogole *et al.*, 2022). Wood is the preferred fuel source in other areas of the country, such as the Limpopo province, where coal is less readily available. In South Africa, an improved wood-fuelled stove is needed in areas where wood is a preferred energy source.

2.5.1 Design of wood-burning stoves

As described in Section 2.4, the purpose of an improved cookstove is to decrease fuel consumption, lower emissions, and achieve higher thermal efficiency than traditional cookstoves or open fires. Improved cookstoves have specific design features to achieve this goal. Overall, the main objective of any cookstove design should be to achieve very high temperatures within

the stove, to ensure complete combustion of combustible gases, and to direct sufficient heat to a cooking vessel (Bryden *et al.*, 2005). These design objectives can be achieved first by including chimneys and enclosed combustion chambers and using the correct fuel and metal cooking pots (Bryden *et al.*, 2005).

The ten principles of woodstove design by Dr Larry Winiarski, as Bryden *et al.* (2005) reported, can be used to finalise any woodstove design. The principles include design features and end-user activities that could influence the stove's performance. The ten principles are summarised below.

i. Insulate the fire.

Insulation surrounding the fire helps keep the fire at a high temperature, resulting in lower smoke emissions. Insulating the fire keeps heat from going to waste by entering the body of the stove rather than the cooking vessel. Lightweight, heat-resistant insulation, such as pumice, refractory bricks, vermiculite or perlite, is suggested.

ii. Add an insulated chimney above the fire.

The addition of a chimney should increase the draught within the stove. Smoke in the chimney will be exposed to the flame, reducing emissions. Increasing the length of the chimney will produce cleaner smoke while decreasing it will focus more hot air on the cooking vessel. The suggested length of the chimney is usually three times its diameter.

iii. Heat and burn the ends of the sticks as they are fed into the fire.

Sticks should be burnt from one side only. The stove should be designed to keep the sticks, or part of the sticks, that are not on fire as cool as possible to minimise smouldering. Less smoke is emitted when the tips are heated first and allowed to burn along the length.

iv. High and low heat is regulated by the amount of fuel fed.

It is suggested that the user only use the fuel required to complete the cooking task. Less fuel will result in less power, and more fuel will result in higher power.

v. Maintain a fast draught through the stove.

Proper draughts achieve a higher stove temperature, resulting in a cleaner fire.

vi. Maintain a suitable draught.

Although a fast draught is necessary for complete wood combustion, it can negatively impact the stove's performance. Too much air can cool the fire, resulting in low thermal efficiency.

vii. Keep a constant cross-sectional area.

Ensuring that the opening into the fire, the spaces through which the air flows and the chimney have the same cross-sectional area can contribute to creating and maintaining an appropriate draught within the stove.

viii. Use a grate in the combustion chamber.

An elevated grate in the combustion chamber ensures airflow beneath the burning sticks, resulting in warmer air reaching the fire and complete combustion.

ix. Insulate the path through which the hot air flows.

Insulating the airflow path inhibits heat transfer between the fire and the stove body. Insulation keeps the flue gas warm, producing higher efficiency in heating the cooking vessel.

x. Use appropriately sized channels to guide airflow.

Smaller channels are more effective in directing heat towards the cooking vessels. Air is forced into the smaller channels and effectively moves closer to the cooking vessels.

Makonese and Bradnum (2018) investigated examples of the influence of design parameters on stove performance. They tested six improved cookstoves' thermal and emission performance, varying the hopper size and the number of secondary air inlets. It was determined that stoves with large hoppers achieved better thermal and emission performance than stoves with smaller hoppers (Makonese & Bradnum, 2018). Two secondary air inlets led to better performance than one or three inlets (Makonese & Bradnum, 2018). The Flamingo™ stove used in this investigation has a small hopper and two secondary air inlets.

2.5.2 Wood as a fuel source

The potential of wood as an energy source is based on its properties and effect on combustion propensity. Properties and characteristics depend on factors such as the species of wood, the moisture content, the location of growth, the part of the tree from which the wood was harvested and the age of the tree (Rowell, 2016). The combustion and emission behaviour of wood species depends on the specific species' properties.

Wood is a biopolymer that consists of cellulose, hemicellulose, and lignin, with little inorganic material and extractives (Rowell *et al.*, 2012). The three components are contained within the cell walls of wood. The primary cell wall contains cellulose, hemicellulose, pectin, and other proteins, while the secondary cell wall only contains cellulose, hemicellulose, and lignin (Mai & Zhang, 2023). Typically, cellulose contributes 40% of the dry weight, while hemicellulose and lignin contribute 20–40% and 10–25%, respectively (Niemz *et al.*, 2023).

Cellulose, a homopolysaccharide, is a significant component of wood, as it determines the characteristics of living wood and the properties of wood as a material (Stevanovic, 2016).

Hemicellulose is similar to cellulose but often has different monosaccharides in its bindings, making them heteropolysaccharides (Stevanovic, 2016). Hemicellulose is important in pulping and drying since it remains in the pulp, unlike the dissolved lignin (Stevanovic, 2016). Lignin, a complex polymer of phenylpropane, acts as a binder between lignocellulosic cells while protecting against external threats such as insects (Mai & Zhang, 2023). The three components degrade at different temperatures when the wood is heated. Hemicellulose typically degrades between 250-340 °C, cellulose degrades between 340-400 °C and, lastly, lignin degrades at temperatures higher than 400 °C (Maake *et al.*, 2020; Poletto, 2016).

Moisture content is generally described as the ratio of the mass of the water and the dry weight of the wood (Thybring & Fredriksson, 2023). The moisture content of wood impacts the thermal, mechanical, and elastic properties (Rowell, 2016). In living wood, the moisture content contributes to elasticity, which protects the wood against environmental factors such as wind (Rowell, 2016). For combustion, the lower moisture content is preferred since higher moisture leads to partial combustion and, in turn, higher smoke production (Pompe & Vines, 1966). Higher moisture content in wood is related to higher CO emissions since moisture inhibits flaming combustion and is also associated with higher PM emissions in wood stoves (Price-Allison *et al.*, 2023).

The calorific value, the amount of energy released per kilogram, decreases as the moisture content increases since energy is used to evaporate the water (Huhtinen, 2005). Wood is usually dried before use to optimise its processing and combustion abilities (Rowell, 2016). The wood can expand as the water is absorbed and shrink as the water is removed, directly affecting the density of the wood (Niemz *et al.*, 2023).

Density impacts the combustion performance of wood. There are four types of wood density due to the varying volume and mass values observed: density at a specific moisture content, oven-dry density, cell-wall density and basic density (Niemz *et al.*, 2023). The density is always a quotient of the mass and volume under specified conditions, for example, the mass and volume of oven-dried wood or the mass and volume of the cell wall. The basic density makes use of the mass of oven-dried wood and the maximum green volume (Niemz *et al.*, 2023).

The density of the cell wall is proportional to porosity, or the void content, as the pore volumes change as the volume of the cell walls changes (Niemz *et al.*, 2023). Density and porosity directly influence the combustion behaviour of wood since higher-density woods will have lower porosity, leading to a lower oxygen supply and a decrease in combustion efficiency (Osvaldova *et al.*, 2023; Wang *et al.*, 2022). It is observed that species with lower porosity tend to self-extinguish due to a lower oxygen supply (Wang *et al.*, 2022).

The combustion performance of wood is also correlated with its thermal properties, such as thermal conductivity, specific heat, ignition time, and thermal expansion (Niemz *et al.*, 2023). The thermal conductivity of wood is a measure of the amount of heat flow through a specific size of wood for a temperature difference of 1 °K (Niemz *et al.*, 2023). Wood is known to have a low thermal conductivity, which leads to a high insulating property (Niemz *et al.*, 2023). The thermal conductivity of wood is related to density – this phenomenon is observed by the lower conductivity of sapwood and the higher conductivity of hardwood (Mauranen *et al.*, 2015).

The specific heat of wood is a measure of the amount of heat needed to heat 1 kg of wood by 1 K (Niemz *et al.*, 2023). The moisture content of the wood directly influences the specific heat of wood, as water has a high specific heat and is independent of the density of the wood (Niemz *et al.*, 2023). The thermal diffusivity of wood is defined as the velocity of heat conduction in the wood (Niemz *et al.*, 2023).

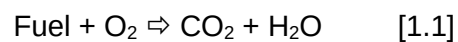
The physicochemical properties of wood, determined from proximate and ultimate analysis, can directly influence combustion and the emissions released when burnt. The fixed carbon content of wood is associated with smouldering combustion, while volatile matter is associated with flaming combustion (Jia *et al.*, 2021). Fixed carbon and volatile matter content is directly linked to the reactivity of the wood. The ultimate analysis results link to emissions - a high nitrogen content in wood will result in higher NO_x emissions, while a higher sulphur content will result in higher SO₂ emissions.

For this project, the focus is on the use of four wood species, namely Sickie Bush (*Dichrostachys cinerea*), Mopane (*Colophospermum mopane*), Leadwood (*Combretum imberbe*), and Black Wattle (*Acacia Mearnsii*). Fire performance property testing has been conducted on Leadwood and Mopane by Maake *et al.* (2020), but limited information is available on Sickie Bush. Leadwood was found to have a longer ignition time (25-153 seconds) when exposed to different heating fluxes, indicating better thermal performance (Maake *et al.*, 2020). Mopane wood has poor thermal performance, indicated by the fast ignition times (5-39 seconds) observed (Maake *et al.*, 2020). Leadwood and Mopane have a thermal conductivity of 0.290 W/(m.K) and 0.258 W/(m.K), respectively (Maake *et al.*, 2020).

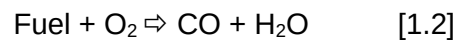
2.5.3 Wood combustion and emissions

Wood combustion consists of four processes: drying and heating, pyrolysis, flaming combustion, and smouldering combustion (Kituyi *et al.*, 2001; Ndiema, 1992). First, the free moisture content in the wood evaporates as the fuel is heated to 100 °C without causing any chemical changes in the wood (Östman *et al.*, 2023). The moisture trapped within the wood cell walls evaporates between 160 °C and 200 °C.

Wood does not burn directly but instead undergoes pyrolysis (Friquin, 2011). Pyrolysis is the thermal degradation of wood without an oxidiser present. This reaction is endothermic and takes place between 225 °C and 500 °C (Bartlett *et al.*, 2019; Östman *et al.*, 2023). The pyrolysis reaction occurs faster in dry samples (Bartlett *et al.*, 2019). During pyrolysis, wood decomposes into combustible gases, condensable liquid tars, solid char, and ash (Bartlett *et al.*, 2019; Friquin, 2011). Tar and combustible gases (e.g. methane and formaldehyde) mixed with air create a gas-phase oxidation reaction, resulting in flaming combustion (Bartlett *et al.*, 2019; Friquin, 2011). Flaming combustion (homogeneous combustion) is typically associated with complete combustion (Reaction 1.1), as seen by lower CO/CO₂ ratios during this phase (Kituyi *et al.*, 2001; Ndiema, 1992).



This reaction leads to the formation of a solid residue on the surface of the wood called char (Östman *et al.*, 2023). The lignin content of wood is responsible for the formation of char since it is more thermally stable than the other wood constituents (Östman *et al.*, 2023). Higher lignin values lead to increased char formation, which limits the ignitability and combustion of wood (Östman *et al.*, 2023). Oxidation of solid chars results in smouldering combustion (heterogeneous combustion) (Friquin, 2011). Smouldering combustion is typically correlated with incomplete combustion, Reaction 1.2, and higher CO/CO₂ ratios (Kituyi *et al.*, 2001; Ndiema, 1992).



The combustion reaction at this stage is slowed due to ash build-up that insulates the char and limits oxygen access (Makonese & Bradnum, 2018). The wood will continue to burn heterogeneously until the fuel or air supply is depleted, after which it will self-extinguish.

During wood combustion, emissions of CO, CO₂, NO_x, SO₂, PM_{2.5}, and PM₁₀ are expected (Sandov *et al.*, 2021). These pollutants are expected from combustion in a cookstove, but the specific emissions are influenced by stove design and the wood properties (Deng *et al.*, 2018; Deng *et al.*, 2023; Huangfu *et al.*, 2014; Kituyi *et al.*, 2001; L'Orange, DeFoort, *et al.*, 2012). Emissions can vary based on the phase of combustion. According to Makonese and Bradnum (2018) poor emission performance was observed during the ignition and smouldering phases of combustion in a cookstove. Considering the design principles in Section 2.5.1, this is expected, as the stove will be burning at low temperatures, leading to incomplete combustion.

After ignition, when the volatile matter within the wood is ignited and flaming combustion commences, the temperature of the fuel bed will rapidly increase and result in lower CO and PM emissions (Makonese & Bradnum, 2018). NO_x and SO₂ emissions are mainly observed during pyrolysis and flaming combustion (Mitchell *et al.*, 2020). These emissions are due to the nitrogen

and sulphur content of the wood that oxidises to form the above products. The CO emission increases again at the end of the char-forming phase when the wood is nearing burn-out due to decreased stove temperatures (Makonese & Bradnum, 2018). During smouldering combustion, smoke is emitted when oxygen becomes the limiting factor, containing H₂O, CO, CO₂, and other VOCs (Östman *et al.*, 2023).

According to Maake *et al.* (2020), Leadwood can emit 423 g/kg of smoke during a flaming time of 33–575 seconds, while Mopane can emit 1 199 g/kg of smoke during 6–595 seconds of flaming combustion. It was observed that 0.0076 kg/kg of CO and 0.83 kg/kg of CO₂ were emitted by flaming combustion of Leadwood (Maake *et al.*, 2020). Mopane was observed to emit 0.0148 kg/kg of CO and 1.30 kg/kg of CO₂ during flaming combustion (Maake *et al.*, 2020). The conclusion can thus be drawn that flaming combustion is less emissive than smouldering combustion.

2.6 User influence

During the operation of any cookstove, the user's actions impact the stove's performance. Although there is a standard operating procedure for stoves in the laboratory setting, it is not sure that the user will adhere to this procedure at home. The effect of the user's handling of the stove must be understood to mitigate the effects through the design.

2.6.1 Ignition of woodstove

The ignition method used in woodstoves influences the performance of the stove. It is reported that the ignition phase of a woodstove sequence relates to the highest emissions of both particulate matter and gaseous emissions and requires a proper ignition method to reduce smoke (Bhattacharya, Albina & Myint Khaing, 2002; Brandelet *et al.*, 2018).

Two ignition methods are commonly used in cookstoves: *top-lit* and *bottom-lit*. The layers in which the fuel is packed and ignited are seen in Figure 2-7 (Brandelet *et al.*, 2018).

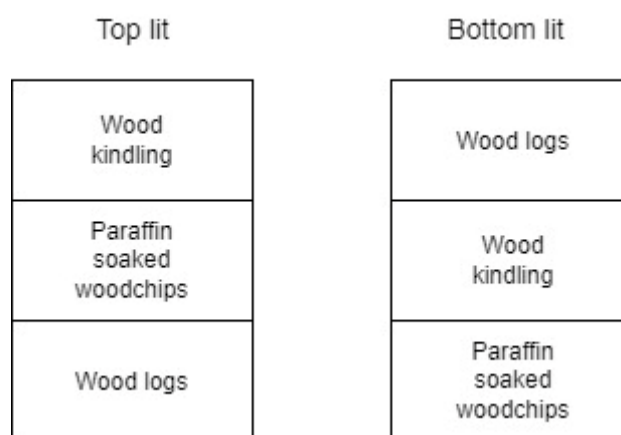


Figure 2-7: Layers used in ignition methods.

The top-lit ignition method requires the wood logs to be placed at the bottom of the fuel bed, with woodchips and wood kindling added to the top, which are ignited and burnt from the top. The bottom-lit method works in reverse, with the woodchips and kindling added to the bottom and the wood logs on top. The bottom-lit method results in lower temperatures throughout the stove, thereby releasing VOCs and water vapour with incomplete combustion and, ultimately, higher smoke production (Makonese *et al.*, 2015).

Although minimal differences in the overall efficiency were observed between the different ignition methods, lower CO and NO_x emissions were observed when the top-lit method was implemented (Brandelet *et al.*, 2018). Brandelet *et al.* (2018) reported a CO emission factor of 41.7 g/kg for the top ignition method, while the bottom ignition resulted in an emission factor of 52.4 g/kg. In coal-burning braziers, lower CO, SO₂, and NO_x emissions are observed at lower ventilation rates when top-lit ignition is implemented (Makonese *et al.*, 2015). The top-lit method is preferred for its lower smoke production.

Since the ignition phase of the testing sequence is the most emissive, the duration of the ignition phase should be minimised. The placement of the wood, along with the kindling, should allow for quick and efficient ignition. For this purpose, testing of appropriate wood and kindling placement was conducted (Figure 2-8). Dry woodchips, paraffin-doused woodchips and kindling were placed in different combinations to determine the most efficient ignition method. The layers of the top-lit method, as shown in Figure 2-5 above, delivered the easiest and fastest ignition.



Figure 2-8: Wood placement and kindling testing (own photo).

2.6.2 Refuelling

Users could require a cookstove to be refuelled during operation, whether the stove design allows it. Refuelling affects the stove's emission performance.

Maddalena *et al.* (2014) found that refuelling resulted in five times the PM emissions typically observed in a coal cookstove. Furthermore, Tryner *et al.* (2014) found that refuelling increased CO emissions. Tryner *et al.* (2014) observed that batches added during refuelling burn quickly, which could explain the increased CO emissions. According to Parsons *et al.* (2022), refuelling significantly impacted the CO and PM_{2.5} emissions, with 9.8 and 1.8 times the baseline CO and PM_{2.5} emissions, respectively.

2.7 Lab-based standardised testing

The testing of improved cookstoves is regulated worldwide by the ISO 19867-1:2018 standard for testing protocols. The Clean Cooking Alliance encourages using the ISO standard in conjunction with procedures established by them and other entities, such as the World Bank. Examples include the Water Boiling Test (WBT) and the Heterogeneous Testing Protocol (HTP). The ISO standard is implemented to ensure that stoves worldwide are tested in the same manner and to ensure adaptability between the methods used for different cookstoves and fuel types (International Organization for Standardization, 2018b).

The standard sets out the necessary measurements to be taken and the calculations that need to be done to determine the required performance factors. Before any testing can be performed, specific requirements must be adhered to. The cookstove itself should be a representative sample of the cookstoves produced: for high-quality control, one stove is sufficient, but for artisan manufacturing and lower-quality control, three or more stoves should be tested (International Organization for Standardization, 2018b). The cooking vessel used for testing should be of appropriate size and similar to that used in real-world settings (International Organization for Standardization, 2018b). The specific fuel type, size, shape and composition for which the stove is designed should be used in the test sequence (International Organization for Standardization, 2018b). It is allowed to use additional fuel, such as kerosene (paraffin), for the start-up (International Organization for Standardization, 2018b). Lastly, the cookstove should be tested according to the designed operating procedure – unless a stove is used differently in field testing, in which case the field testing method should be used (International Organization for Standardization, 2018b). It is of utmost importance that the fire in each test is ignited in a reproducible manner, which can be replicated in any area using standard materials.

2.7.1 Thermal performance testing: WBT or HTP.

According to the ISO standard, any cookstove's thermal efficiency is presented as the energy efficiency and cooking power. The WBT procedure from the Clean Cooking Alliance is often used for thermal performance tests. During the procedure, the amount of water evaporated from an aluminium pot is measured when placed on a cookstove, and the pot lid is removed for the test duration (Clean Cooking Alliance, 2014). The test sequence includes three phases: high power

(cold start), high power (hot start) and low power (simmer) (Clean Cooking Alliance, 2014). The remaining fuel is removed from the stove after each phase.

Another procedure to determine the thermal efficiency of a cookstove is the HTP (Robinson *et al.*, 2010). The testing sequence consists of the same three phases as the WBT. The differences between the two include not removing fuel from the stove during the test and performing the test with the pot lids in place. The HTP aims to duplicate cooking practices, which is why pot lids are used in the test.

Although the two testing methods deliver similar thermal efficiency results, the WBT focuses on one specific task, while the HTP includes a broader range of conditions in the test sequence (Makonese *et al.*, 2011). The difference between the two tests lies in the data analysis, as well as the use of a pot lid, and can be seen in the firepower, fuel consumption, and turn-down ratio (Makonese *et al.*, 2011). The HTP is used due to its ability to generate performance curves over a wide range of conditions rather than focussing on one task (Makonese *et al.*, 2011).

The weight of the water before and after the test sequence is measured and used to calculate the useful energy delivered. The useful energy is calculated as the heat gained by the pot and the water content. However, for the HTP, the difference should be slight since evaporation is limited. For multi-pot stoves, each pot should be weighed, and the useful energy of each pot should be determined (International Organization for Standardization, 2018a). The cooking power of the stove is calculated using the useful energy delivered and the cooking time. The thermal efficiency of a cookstove can be calculated by dividing the useful energy delivered by the product of the consumed fuel mass and the LHV of the fuel (International Organization for Standardization, 2018a). Thermal efficiency measures the energy absorbed by water in the cooking pot and by the pot.

Thermal performance can be further investigated by calculating the efficiencies of the system, heating, and combustion (Sumbane-Prinsloo *et al.*, 2021). System efficiency is calculated using the Siegert formula and is a measure of the effective heat delivered from combustion in the stove, taking only stack heat loss as an energy loss from the system (Sumbane-Prinsloo *et al.*, 2021). Heating efficiency is an indicator of the performance of a space heater by calculating the amount of heat lost to the surrounding environment (Sumbane-Prinsloo *et al.*, 2021). The efficiency of combustion is an indication of the quality of combustion since CO/CO₂ ratios are taken into account (Sumbane-Prinsloo *et al.*, 2021). This is excluded from the scope of this study since the Flamingo™ stove is classified as a stove used only for cooking.

The measurements necessary to determine the thermal efficiency of a cookstove can thus be summarised as follows:

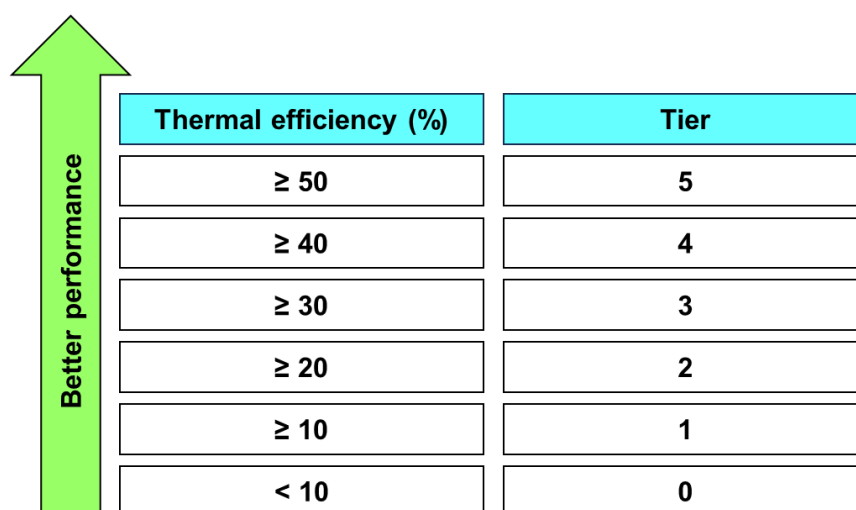
- The initial mass of water in the cooking pot (kg).

- The final mass of water in the cooking pot (kg).
- The initial water temperature in the cooking pot (°C).
- The final temperature of the water in the cooking pot (°C).
- Time at the start of the test sequence (s).
- Time at the end of the test sequence (s).
- Mass of wood fed to the stove (kg).

Additional values for the necessary calculations, such as the higher and lower heating values, are determined from the analysis of the samples before the test sequence.

The thermal performance of a cookstove is related to the fuel usage. The wood burning rate within the cookstove can be determined by combustion testing or thermogravimetric analysis of the fuel (Sumbane-Prinsloo *et al.*, 2021). Low burning rates are favourable, as less fuel will be consumed. Higher fuel consumption rates lead to higher PM emissions (EPA, 2023d).

Based on the thermal testing of the cookstoves, the stoves can be classified according to tiers. The stove tiers, or voluntary performance targets, are set by the International Organization for Standardization (2018b). The tiers based on thermal performance are shown in Figure 2-9.



Thermal efficiency (%)	Tier
≥ 50	5
≥ 40	4
≥ 30	3
≥ 20	2
≥ 10	1
< 10	0

Figure 2-9: Voluntary performance standards (tier classification) of cookstoves based on thermal efficiency. Adapted from International Organization for Standardization (2018b).

Tier zero represents open fires and older cookstoves, while tier 1–4 indicates cookstoves with minor improvements to older cookstoves, and lastly, tier 5 represents the best existing cookstove technology (International Organization for Standardization, 2018b). Each performance factor, such as thermal and emission, is evaluated and reported individually.

2.7.2 Emission performance testing

According to the International Organization for Standardization (2018a), the emission performance of a cookstove is measured using emission factors and emission rates for each

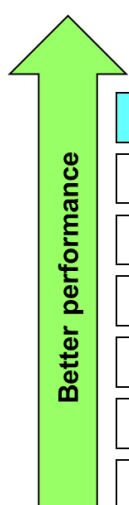
pollutant present in the flue gas. The emission factor of each pollutant is calculated as the total mass of the pollutant emitted during the test sequence per the useful energy delivered (International Organization for Standardization, 2018a). The emission factor can be presented in terms of the fuel mass used.

The emission rates of the various pollutants are calculated by dividing the total mass of the pollutant during the sequence by the total duration of the test sequence. Continuous emission data for the test sequence should be recorded every ten seconds for use in calculations (International Organization for Standardization, 2018a).

The necessary measurements needed to quantify the emission performance of the stove are thus summarised as follows (International Organization for Standardization, 2018a):

- PM_{2.5} mass or concentration (filter or continuous measurements)
- CO mass/concentration.
- CO₂ mass or concentration.
- NO_x mass or concentration.
- SO₂ mass or concentration.

Notably, most equipment used for continuous emission measurements reports emissions of different pollutants in ppm. To calculate the mass of each pollutant for use in emission factor calculations, a mass balance is usually performed using carbon (Makonese *et al.*, 2017). It is necessary to consider the moisture content of the flue gas during these calculations. Gas analysers report emission values on a dry basis, and thus, the values should be converted to a wet basis. The stoves are once again classified into tiers based on their emission performance (Figure 2-10).



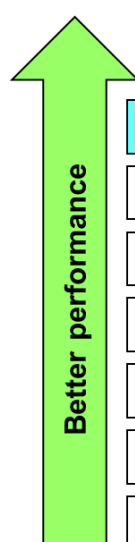
CO (g/MJ)	PM2.5 (mg/MJ)	Tier
< 3.0	< 5	5
< 4.4	< 62	4
< 7.2	< 280	3
< 11.5	< 481	2
< 18.3	< 1030	1
> 18.3	> 1030	0

Figure 2-10: Voluntary performance standards (tier classification) of cookstoves based on emission performance. Adapted from International Organization for Standardization (2018b).

2.7.3 Safety testing

The standard specifies how the safety of a cookstove should be evaluated. The stove is tested for sharp edges, tipping, and fuel containment when the stove is not lit (International Organization for Standardization, 2018b). Further dangers are measured when the stove is lit, including the danger of surface temperatures, flames that exit the stove or fuel chamber, and the temperature of any handles or controls (International Organization for Standardization, 2018b). The safety of a cookstove is evaluated on a point basis – ten safety procedures are carried out, each receiving a point between one and four (four being the best). The points for each procedure are multiplied with a weighting factor to calculate an overall safety score (International Organization for Standardization, 2018a).

The overall safety score is classified according to a tier (Figure 2-11).



Safety score	Tier
≥ 95	5
≥ 86	4
≥ 77	3
≥ 68	2
≥ 60	1
< 60	0

Figure 2-11: Voluntary performance standards (tier classification) of cookstoves based on safety.
Adapted from International Organization for Standardization (2018b).

Thus, a cookstove's overall performance rating combines thermal efficiency, emissions and safety factors. The safety rating is also excluded from the scope of this study.

2.8 Previous studies

In recent years, extensive research has been done on various cookstoves using different fuels. Table 2-3 summarises a few of the recent studies conducted on wood-burning improved cookstoves.

Table 2-3: Previous studies on woodstoves and their findings.

Study title	Author	Fuel	Stove type	Key findings
Clean cooking with downdraft biomass gasifier cookstove: Effect of gasifier performance.	Sutar <i>et al.</i> (2023)	<i>Leucaena leucocephala</i> , <i>Syzygium cumini</i> and <i>Azadirachta indica</i> . 2 cm in length; 9-20 mm diameter	Downdraft gasifier. Forced draft.	High cookstove efficiency observed in cookstove - between 26%-44% for a 4-kW stove. Turn down ratio between 2.2-2.8. Emission factors are dependent on the fuel species used.
Thermal performance and heat storage behaviour of three pots improved the cookstove.	Rathore <i>et al.</i> (2022)	<i>Prosopis juliflora</i>	Three-pot stove with two chimneys. Made from bricks and cement.	Thermal efficiency of 34.45%. Power rating of 1.72 kW. The average CO, CO ₂ and PM _{2.5} were recorded as 6.3 mg/MJ, 628 ppm and 170 mg/MJ, respectively.
Determination of emission factors for climate forcers and air pollutants from improved wood-burning cookstoves in Mexico.	Padilla-Barrera <i>et al.</i> (2019)	<i>Quercus bicolor</i>	Mexican Patsari stove.	The emission factor of CO ₂ was 1 364 g/kg. The emission factor of PM _{2.5} was found to be 2.11 g/kg.
Cookstove Emissions and Performance Evaluation Using a New ISO Protocol and Comparison of Results with Previous Test Protocols	Champion <i>et al.</i> (2021)	Red oak, hardwood pellets, hardwood charcoal.	LPG, pellet, wood fan, rockets, three stone fire and charcoal	ISO protocol is better for lab-based, controlled testing – better repeatability. FST is better for field testing. ISO inclusion of all combustion phases (like ignition and shutdown) influences stove tier performance.

Study title	Author	Fuel	Stove type	Key findings
Thermal performance of three improved biomass-fired cookstoves using fuel wood, wood pellets and coconut shell.	Sonarkar and Chaurasia (2019)	Wood chips (WC) Wood pellets (WP) Coconut shells (CS)	Top-lit updraft stove.	The efficiency of three fuel types for high-power cold start sequences – WC = 25%, WP = 26%, and CS = 27%. Firepower was between 4 247-4 277 W for each fuel type. Specific fuel consumption between 0.15-0.16 g/L. Mean emission concentrations for PM _{2.5} were found to be 1310 µg/m ³ . Also, the Purti and Mpurti stoves performed much better.
Test Kitchen studies of indoor air pollution from biomass cookstoves.	Grabow <i>et al.</i> (2013) Aprovecho Research Centre	Douglas fir sticks and pellets	Three stone Rocket stove TLUD	With the kitchen door open: <u>Average PM concentration (µg/m³)</u> TSF – 1 145 Rocket – 973 TLUD – 54 <u>Average CO concentration (ppm)</u> TSF – 43 Rocket – 31 TLUD – 4
Fuel use and emissions performance of fifty cooking stoves in the laboratory and related performance benchmarks.	MacCarty <i>et al.</i> (2010)	Kiln-dried Douglas fir	50 different stoves	Determined the following benchmarks for the WBT to boil 5 L of water: Energy use – less than 15 MJ. CO – less than 20 g emitted. PM – less than 1 500 mg emitted. Fuel – less than 30 MJ. Stoves meeting the benchmark include the cast iron rocket stove, the insulated brick rocket stove and the metal skirted rocket stove.

Study title	Author	Fuel	Stove type	Key findings
Effects of moisture content in fuel on thermal performance and emission of biomass semi-gasifier cookstove.	Huangfu <i>et al.</i> (2014)	Cylindrical wood pellets. Length of 2 cm and 0.8 cm in diameter.	Top-lit updraft stove. Natural draft stove.	Effect of moisture content on emissions and thermal performance - higher thermal efficiency from fuel with higher moisture content. MC of 22.1% had an efficiency between 25%-35%. The burning rate is lower for higher moisture content. CO emission factor decreases with increasing moisture content. $EF_{CO} = 4.25 \text{ g/MJ}$ for 5.9% MC. PM emission factor decreases for higher MC. $EF_{PM} = 550 \text{ mg/MJ}$.
Influence of testing parameters on biomass stove performance and development of an improved testing protocol.	L'Orange, DeFoort, <i>et al.</i> (2012)	Not reported – different geometries, moisture content.	Not reported.	Fuel size does not significantly impact CO emissions but does influence PM emissions. Increased wood size leads to lower PM emissions and less refuelling. 20-25 g of CO emitted from two testing methods.
Field-based performance evaluation of optimised improved biomass mud cookstoves in rural India.	(Wathore <i>et al.</i> , 2023)	Wood from the surrounding area of Kotwariya Village. No specific species was mentioned.	Pavak - 1 and Pavak – 2 stoves. Improved mud-based stoves.	Thermal efficiency in the laboratory of Pavak-1 and Pavak-2, respectively, 27.5% and 27.1%. The CO emission factors for Pavak-1 and Pavak-2 were 18.7 g/kg and 10.7 g/kg, respectively. Much higher EF was observed during field testing (84 g/kg and 95 g/kg). PM emission factors of 1.38 g/kg and 1.01 g/kg were observed. Performance in field testing and lab testing differs.

Cookstove efficiency varies between different stove designs and fuel types. Table 2-3 shows that downdraft gasifier stoves show efficiencies between 26-44%, while a three-pot stove with two chimneys reached a 34% efficiency (Rathore *et al.*, 2022; Sutar *et al.*, 2023). Increased efficiency is observed with increased wood moisture content, which also reduces the burn rate. From the studies summarised above, it is concluded that overall, the thermal efficiency of a wood cookstove lies between 25%-35%.

The emission factors for CO are around 1.01 to 2.11 mg/kg and 550 mg/MJ, depending on the emission factor calculation base. The emission factors for CO range between 10.7 and 18.7 g/kg, or 4.25 g/MJ. It was also observed that wood size affected the PM emissions but not CO emissions (L'Orange, Volckens, *et al.*, 2012; L'Orange, DeFoort, *et al.*, 2012). Emissions are reliant on fuel type, as seen by the lower emissions of CO when using pellets, dried wood and coconut shells compared to raw wood chips (Sonarkar & Chaurasia, 2019).

The testing protocol used can also influence the performance parameters of a stove. Stoves tested in lab-based studies show increased performance compared to field-based testing (Champion *et al.*, 2021). A broad summary can be made, stating that three factors affect the overall performance of the stove: the fuel type, the stove design, and the user (or testing) protocol.

From the above studies, no stoves similar to the Flamingo™ stove have been tested. Including an integrated oven is a feature not often seen in cookstoves. The use of South African wood species, which is seldom reported, was also explored. The effect of varying fuel species, specifically those used in South Africa, thus requires further exploration. User behaviour, such as refuelling and cooking habits, is rarely studied. The Flamingo™ stove's continuous refuelling and cooking using an oven provides the opportunity for further study.

Over the past decade, numerous studies have been conducted concerning various stove designs, fuel types and performance evaluations. Conducting a comprehensive review of this extensive literature exceeds the scope of the present study. The stove design, the fuel type and user behaviour influence the overall performance of any cookstove. These factors can be presented in multiple variants.

The point of departure for this investigation was the availability of a model of the Flamingo™ stove, a novel design that departs from conventional designs in using twig-size fuel pieces, continuously fed, a twin hob and an incorporated oven. The key variable investigated was the effect of fuelwood species rather than a comparison with other stove types. In our investigation, variation in fuel size is constrained by artificially creating uniform stick sizes (rectilinear sawn sticks). User behaviour is constrained by adopting a uniform fuel feed rate at five-minute intervals.

This tightly controlled experimental design has allowed a comparison of the fuel wood species on the thermal and emission behaviour. This design represents only one aspect of the stove technology as a potential domestic appliance. Real-world behaviour will comprise many other variants that could be explored in further laboratory investigations.

2.9 Summary

This chapter provided background information on domestic energy use in South African households. Wood was identified as the primary energy source in low-income households in the Limpopo province of South Africa. The indoor use of wood results in indoor air pollution, potentially harming human health and the environment, specifically local air quality. Since solid fuel and traditional stoves cannot always be avoided due to socio-economic conditions, intervention of different means is necessary.

Viable alternatives to open fires and traditional solid-fuel stoves are *clean cookstoves* (CCS), also called *improved cookstoves* (ICS). CCS enable low-income households to use solid fuels as always, but with reduced impacts on their health or local air quality. The influence of South African wood species on cookstoves' emission and thermal performance has yet to be widely reported. The combination of wood stove and fuel should be compatible, and it is necessary to test the use of the Flamingo™ stove with local South African wood species.

Laboratory cookstoves can be tested using different protocols, but the heterogeneous testing protocol (HTP) simulates real-world cooking practices. The stove testing results should be consistent with emission standards set by entities such as the World Bank.

CHAPTER 3 EXPERIMENTAL PROCEDURES

Chapter 3 describes the methods used in the study. Section 3.1 discusses the wood origin, after which the wood size preparation is described. In Section 3.2, the characterisation procedures are discussed. Section 3.3 covers the experimental procedures for stove testing. The data analysis is discussed in Section 3.4. Sections 3.5, 3.6 and 3.7 discuss data quality, assurance, scheduling, and ethical clearance.

3.1 Wood species identification, sourcing and size preparation

Based on previously conducted community surveys, four popular wood species were identified for use in this study. The selected species are popular wood species used in rural villages in Limpopo as fuelwood (Makhado *et al.*, 2009; Mudau, 2023). This was further emphasised through personal communication from Mr Khuthadzo Manyatsha, a PhD candidate specialising in wood and cookstove use in Limpopo. The criteria used to determine the species included location, specifically within the Limpopo province and the frequency of use by local communities.

Leadwood (*Combretum imberbe*) trees are protected under the National Forests Act (Act 84 of 1998). The act permits the use of fallen twigs or wood pieces, which aligns well with the intended use of the Flamingo™ stove, as it was designed to operate as a twig stove. Despite its protected status, it remains a preferred fuelwood among rural communities. Testing of this species for this evaluation is not intended to imply that it should be harvested locally or commercially as an energy source.

All four selected wood species were sourced from one supplier to ensure consistency. *Firewood Factory*, a Tswane-based firewood supplier, was the closest supplier to Potchefstroom, which could supply the required amount of wood at once.

The wood was received as large firewood logs in 15 kg bags. The logs were cut into uniform-sized rectangular cuttings to limit variability brought on by airflow changes due to different wood sizes (Makonese & Bradnum, 2018). The wood cuttings do not represent real-world applications but are used to limit additional experimental variables and ensure repeatability. The wood was cut to a dimension of 15 x 15 x 250 mm (Figure 3-1). A cross-sectional size of 15 mm was chosen for comparability with previous studies and protocols (Clean Cooking Alliance, 2014). The stove burn-in, described in Annexure A, was also used to determine the appropriate size of wood (Figure A-3). JMB Timbers in Potchefstroom cut the wood, and upon return, it was observed that the wood cuttings were not exactly 15 mm in cross-sectional diameter. Leadwood had a width closer to 17 mm, as seen in Annexure B. Leadwood has a high density and hardness, making it difficult to cut. The wood was stored in airtight containers to inhibit moisture absorption from the

surrounding environment. The necessary batch was removed before the start of each experimental sequence.



Figure 3-1: Mopane wood cuttings used in the Flamingo™ stove tests.

A representative sample was taken for physicochemical analysis and sized to <1 mm. A representative sample was taken by removing four logs, at random, from each of the bundles, as seen in Figure 3-1. Each bundle is equal to the cuttings of one 15 kg bag. The size reduction to <1 mm was conducted by cutting the cuttings into smaller pieces, using a bandsaw, to fit into the hammer mill. The samples were passed through a Trapp TRF600 Hammer Mill. The random cuttings were mixed as they were passed through the mill. The cuttings from the hammer mill were passed through a pulveriser (Fritsch Pulverisette 14) and sieved to <1 mm. For each species, a 20 g sample was weighed and stored in sealed bags to limit moisture absorption. The samples were then submitted to the relevant laboratories, NWU or Bureau Veritas, for analysis.

3.2 Wood characterisation and procedures

The wood's proximate and ultimate analysis was outsourced to Bureau Veritas South Africa, a South African National Accreditation System-accredited laboratory. The fibre analysis was conducted at North-West University's laboratory.

All physicochemical analyses are conducted according to ISO and ASTM standard methods as presented in Table 3-1. For fibre and calorific value (CV) analysis at the NWU, 5 g of each species was used at a size of <1 mm.

Table 3-1: Standards used as a reference for different sample analyses.

Analysis	Description	Standards
Proximate analysis (Bureau Veritas)	Ash (wt.%)	ISO 1171:2010
	Moisture (wt.%)	ISO 11722:1999
	Volatile matter (wt.%)	ISO 562:2010
	Fixed carbon (wt.%)	(by difference)
Ultimate analysis (Bureau Veritas)	Carbon (wt.%)	ISO 12902- CHN
	Nitrogen (wt%)	ISO 12902- CHN
	Hydrogen (wt%)	ISO 12902- CHN
	Sulphur (wt%)	ISO 19579:2006
	Oxygen (wt%)	(by difference)
Fibre analysis (NWU)	Hemi-cellulose (wt%)	ASTM D1103-96: 2016
	Cellulose (wt%)	
	Lignin (wt%)	
Calorific value analysis (NWU)	CV (MJ/kg)	ISO 18125:2017

3.2.1 Procedures of non-standard analyses

The determination of the wood density is classified as a non-standard analysis since it is not assigned an ISO or ASTM standard procedure.

Wood density

The density of the wood is determined by measuring the dimensions of each wood cutting, assuming a rectangular cuboid shape, and weighing them individually. The wood was measured using a Vernier Calliper and weighed with a balance sensitive enough to read to the gram. This is repeated five times for each species, using five randomly sampled cuttings. Due to slight deviations in size, as referred to in Section 3.1, a lower number of repeats resulted in inaccurate results. The following calculation was used to determine the density.

$$\rho = \frac{m_{cutting}}{V} \quad (3-1)$$

where ρ is the density (kg/m³), $m_{cutting}$ is the mass (kg) of the cutting, and V is the volume (m³) calculated as $l \times w \times h$.

Linear regression of lignin and density

The following linear regression equations determined the relationship between lignin and the density of the wood species (Equations 3-2 to 3-4).

$$\hat{y} = a + bx \quad (3-2)$$

$$a = \bar{y} - b\bar{x} \quad (3-3)$$

$$b = \frac{\sum(xy) - \frac{\sum x \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \quad (3-4)$$

3.3 Stove testing procedures

3.3.1 Materials

Table 3-2 is a summary of materials used in the testing sequence apart from the wood; this includes cleaning materials, calibration gases, ice and ignition materials.

Table 3-2: List of test materials and calibration gases.

Material	Source	Details	Use
Wood cuttings	-	Refer to Chapter 3	Fuel
Ice	NWU Lab		Ice baths
Paraffin	Builder's Warehouse	Powafix	Firestarter
Acetone	Redspot Chemicals	-	Cleaning
Pine wood chips	Sappi	-	Firestarter
Gases			
Nitrogen	Air Liquide	Purity > 99.999%	Dilution gas Zero calibration
NO	Air Liquide	288 ppm, N ₂ balance	Span calibration
SO ₂	Air Liquide	530 ppm, N ₂ balance	Span calibration
CO ₂	Air Liquide	20.4 vol%, N ₂ balance	Span calibration
CO	Air Liquide	991 ppm, N ₂ balance	Span calibration
O ₂	Air Liquide	21.2 vol%, N ₂ balance	Span calibration

3.3.2 Cookstove identification, characterisation and operation

The Chemical Engineering Department provided the stove technology as part of their larger stove/fuel research agenda. A Flamingo™ stove prototype has been made available for research purposes. It had not been tested previously and had novel features not often seen in other cookstove models. The primary design principle of the stove was to use twigs as fuel while serving the needs of the intended users. Sound engineering design principles would achieve secondary considerations of improved thermal efficiency and minimising emissions; evaluating the latter properties became part of the objectives of this investigation.

The commissioning of the stove included fitting the stove to the existing experimental set-up. Equipment adjustments were made to fit a smaller chimney, piping was shortened as needed, and the laboratory was re-arranged to fit the stove better. Commissioning runs were done to inspect the set-up and ensure all instruments functioned correctly.

Combustion experiments were conducted using a novel cookstove, designed to combust twig-sized wood pieces. The Flamingo™ stove (Figure 3-2) was designed by entrepreneurs Doubt Rusenga and Khulani Dewa. The stove, which weighs approximately 37 kg, has a hopper, an air inlet, a combustion chamber, a secondary air inlet, two hobs and a chimney. A novel feature of this specific stove is the oven and a flap device to regulate heat flow alternately between the second hob and the oven. Laboratory performance testing of the Flamingo™ stove has not been done previously.



Figure 3-2: The Flamingo™ stove with dimensions.

The stove has a small fuel hopper and combustion chamber and requires refuelling at regular intervals. The stove was designed to combust twigs or small biomass pellets. The combustion chamber has a grate placed at an angle to enable the fuel to slide further into the fire. The air inlet, located underneath the hopper, can be adjusted to regulate the air supply to the stove (Figure 3-3). The firepower in the stove is regulated by adjusting the air inlet rather than by regulating the fuel load. The top surface of the stove has two cooking hobs.

Figure 3-3 shows the air inlet slider and the different openings utilised during each testing sequence.

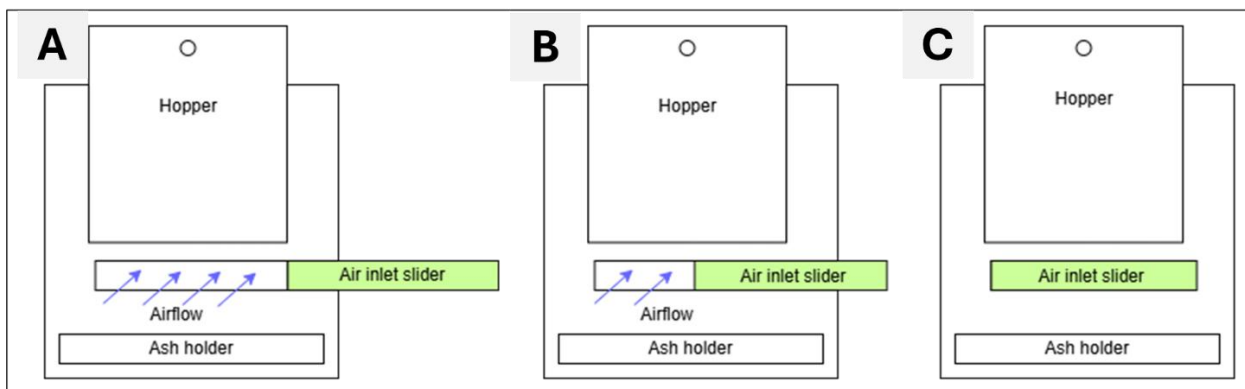


Figure 3-3: Air inlet slider positions.

In Figure 3-3A, the air inlet is fully open – the slider is pushed fully to the right. This position is used during ignition and for the high-power phase. In Figure 3-3B, the air inlet is halfway open and used as the stove’s medium power setting. Lastly, Figure 3-3C shows the air inlet fully closed, which is used as the low-power setting. Leakages around the ashtray and the entrance of the fuel hopper provide sufficient air for combustion despite the air slider being 100% closed.

The use of the oven is regulated by a control flap between the two cooking hobs. The flap controls the path through which the air flows. A diagram of the flap from the side while horizontal is shown in Figure 3-4. The flap has an opening equal to 20% of the flap area, allowing unimpeded airflow over the top of the oven directly to the chimney to regulate the draught when the flap is in the vertical (oven in use) orientation. This bypass flow allows for a positive draft through the stove even in low flow conditions.

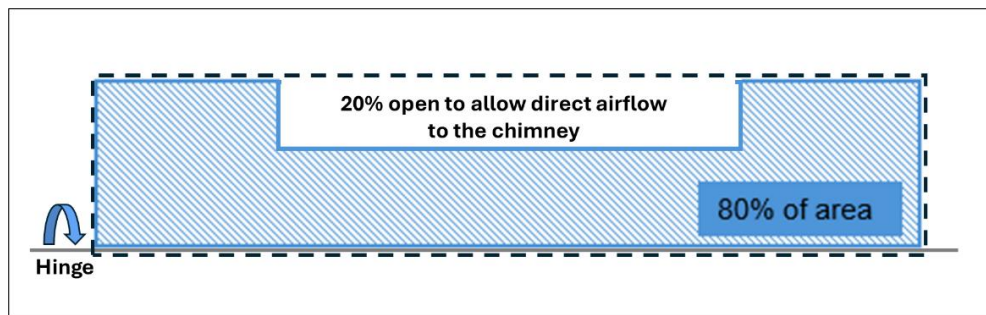


Figure 3-4: Regulating flap of oven.

When the flap is in the horizontal position, the configuration shown in Figure 3-5, heat flows below the two hobs and over the top of the oven. The entrance to the channel leading down the side and beneath the oven is 80% blocked. In this case, both hobs will reach high temperatures for rapid cooking, and the oven will be heated to a limited extent, mainly on the top surface.

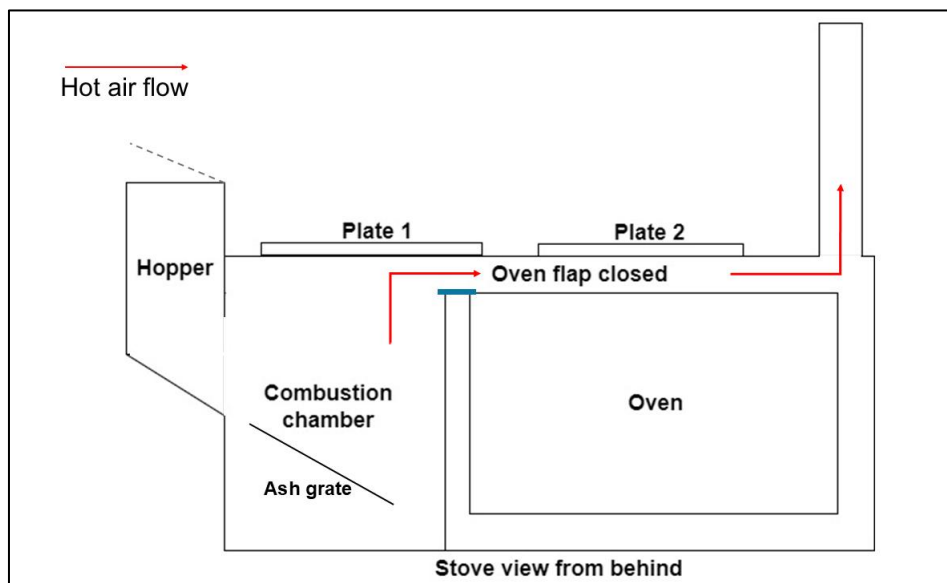


Figure 3-5: Stove configuration when the oven is not in use.

When the flap is vertical, the hot air flow is diverted to flow around the sides and beneath the oven, allowing its use for baking or roasting (Figure 3-6). The first hob will be heated as before, while the second hob will operate at a lower temperature since it is heated by a reduced airflow of ~20%. In this mode, the second hob may be used for simmering.

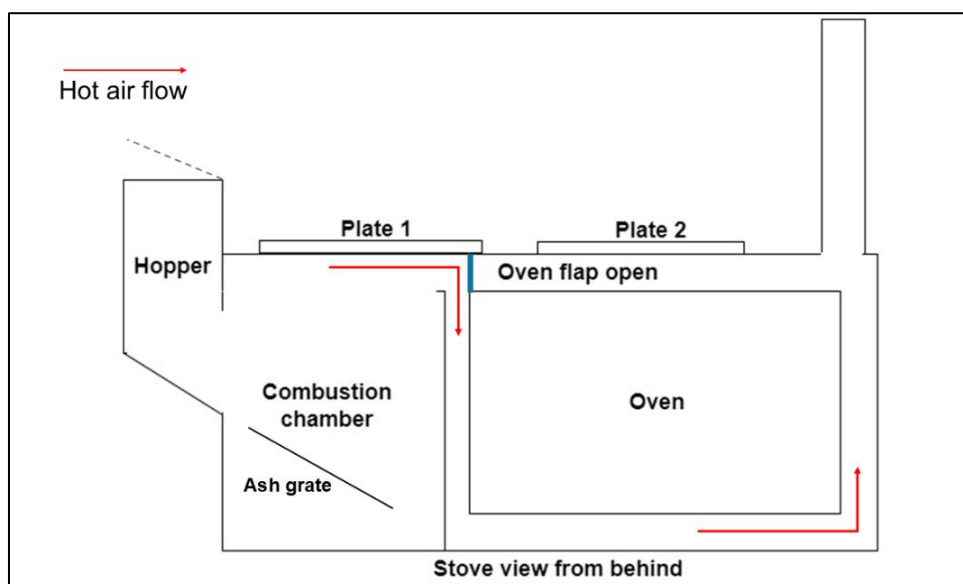


Figure 3-6: Stove configuration when the oven is in use.

3.3.3 Experimental set-up and equipment

Figure 3-7 is a schematic of the complete experimental set-up comprising the stove, mass, emission and temperature monitoring equipment.

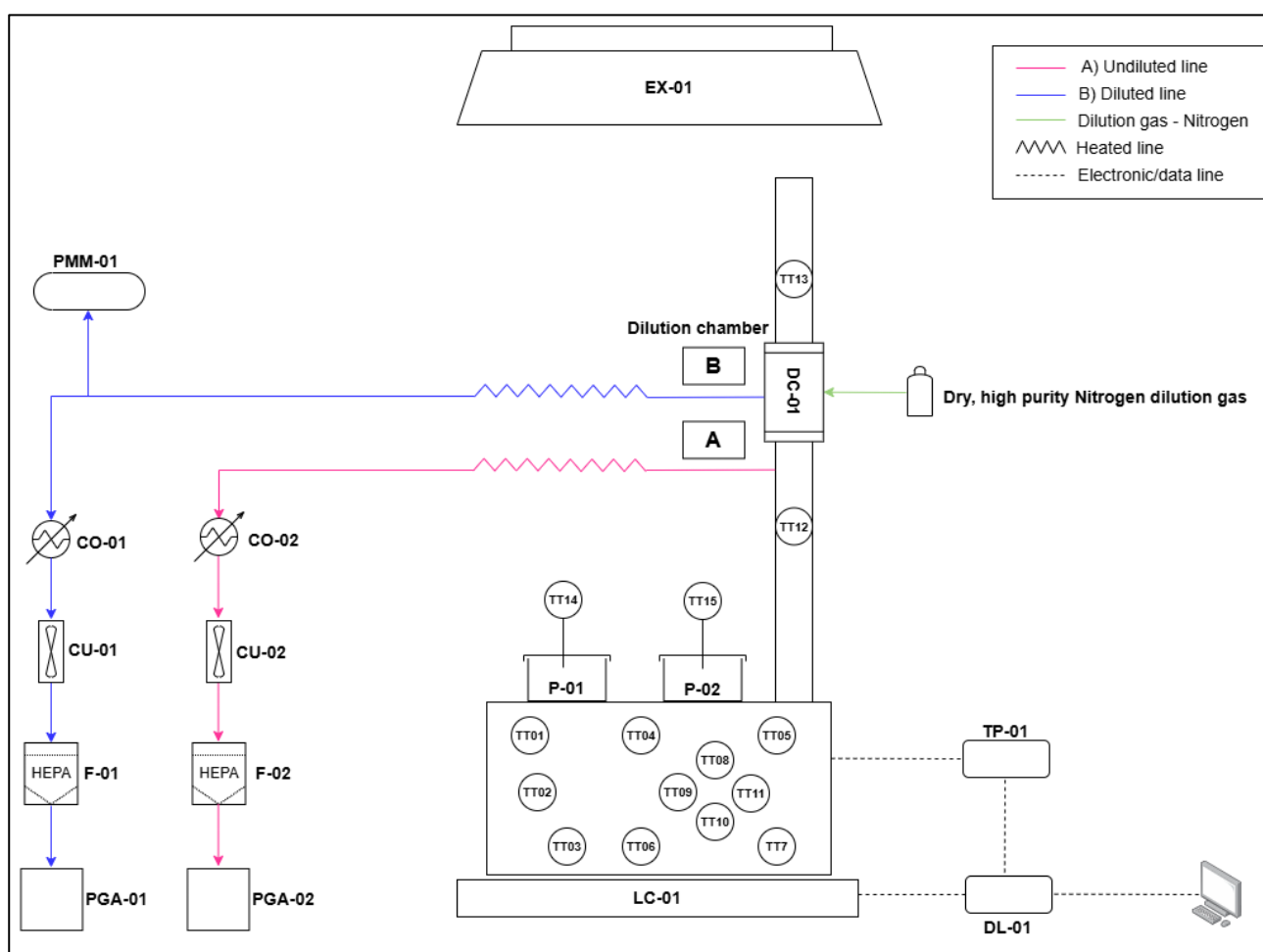


Figure 3-7: Experimental set-up.

Table 3-3 is an equipment list detailing the specific equipment as shown in Figure 3-7.

Table 3-3: Equipment list.

Legend	Instrument	Make and model
CO-XX	Ice bath	-
DL-01	Datalogger	Campbell Scientific CR1000X
CU-01	Conditioning unit	M&C PSS10
CU-02	Conditioning unit	M&C PSS5C
DC-01	Dilution chamber	Manufactured inhouse
Ex-01	Extraction fan	-
F-01	HEPA Filter	Savillex Filter Assembly
F-02	HEPA Filter	Savillex Filter Assembly
LC-01	Loadcell	Minebea Intec Combix 1
P-XX	Pot	Hart 2 L aluminium pots
PGA-XX	Portable gas analyser	Horiba PG350
PMM-01	Particulate matter monitor	DustTrak II: 3530
TP-01	Thermoplex	Campbell Scientific AM25T
TT-XX	Thermocouples	Wika K-type 13 mm Thermocouples

3.3.3.1 Mass measurement equipment

Mass measurements were performed using the load cell. The load cell is sensitive enough to read 0.001 kg. The mass measurements were recorded every 10 seconds. The load cell is connected to a data logger, which logs the data points. The data is accessed using LoggerNet for analysis. The data obtained from the load cell was used to determine the stove's combustion rate and energy output.

The load cell was used to determine only the fuel mass, not the masses of the instruments, pots, or water content. A separate balance weighed the pots and water before and after the testing sequence.

3.3.3.2 Temperature measurement equipment

Thirteen thermocouples measured the temperatures within the stove. The positions of the thermocouples throughout the stove can be seen in Figure 3-8.

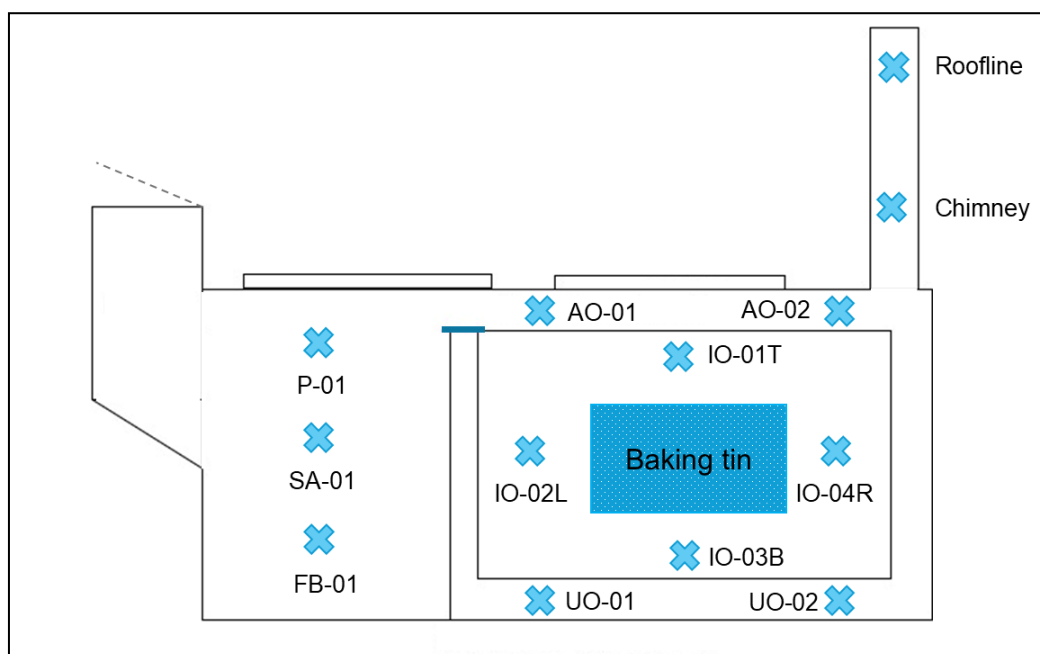


Figure 3-8: Thermocouple positions.

The thermocouples read the temperature of the fuel bed, the secondary air, the air around the oven, and the temperature in the oven. The labels of each thermocouple and the measurement points are summarised in Table 3-4.

Table 3-4: Thermocouple placement and labels.

Thermocouples			
P-01	Hob probe	UO-02	Under the oven on the right
SA-01	Secondary air	IO-01T	Inside oven 1 (top)
FB-01	Fuel bed	IO-02L	Inside oven 2 (left)
AO-01	Above the oven on the left	IO-03B	Inside oven 3 (bottom)
AO-02	Above the oven on the right	IO-04R	Inside oven 4 (right)
UO-01	Under the oven on the left	Roofline	At the end of the chimney
Chimney	Lower in the chimney		

The oven contained a standard baking tray covered in aluminium foil. This was done to prevent interference with the radiant heat from different oven sides. The thermocouples read the temperature of only one side of the oven.

The thermocouples were connected to a Thermoplex, which connected the thermocouples to the datalogger and LoggerNet. Measurements were taken every second and averaged every 10 seconds.

3.3.3.3 Emission sampling and measurement equipment

Flue gas is sampled from the chimney in two parallel streams, referred to as Sample A and Sample B (see Figure 3-7). Sample A was drawn directly from the chimney without dilution for gas analysis. This sampled gas stream was ducted through an ice bath, an M&C conditioning unit to remove any residual moisture and a HEPA filter to remove PM before entering a Horiba gas analyser (Figure 3-9). The species measured were NO_x, SO₂, CO, CO₂ and O₂.

Sample B was extracted using a custom-designed diluter. The diluter injects a jet of dry nitrogen across the stack into a receiving port. This sample stream flow was split between a DustTrak PM monitor and a second instrument array, the same as for Sample A. The only species used from this (Sample B) gas analysis was the CO₂ concentration, which determined the dilution ratio induced by the adjustable dry nitrogen injection.

The two flue gas analysers extract samples at 0.4–0.5 L/min. The analysers have maximum detection limits for each pollutant (Table 3-5). The gas analysers were calibrated within these limits using the calibration gases shown in Table 3-2.

Table 3-5: Horiba analyser gas ranges.

Gas	Maximum gas limits on PG-350
NO _x	2 500 ppm
SO ₂	1 000 ppm
CO	5 000 ppm
CO ₂	30 (vol%)
O ₂	25 (vol%)

The data points were recorded at 10-second intervals. Data logging commenced 5 minutes before ignition to record ambient air concentrations and ensure the proper functioning of the instruments. The data from the analysers were logged on a memory card and extracted to a computer after the run.



Figure 3-9: Horiba PG350 gas analyser display.

A TSI DustTrak II: 3530, a light-scattering particle counter, was used to determine the concentration of particulate matter (PM). This instrument can read particulate matter concentrations between 0.001 and 400 mg/m³. This instrument can distinguish between different PM sizes using different impactors on the sample inlet (e.g. PM_{2.5} or PM₁₀). Size-selective inlets were not used for these tests. Thus, the DustTrak monitored total suspended particles (TSP).

A diluted, cooled gas stream (Sample B) protects the PM monitor from vapour condensation (VOCs or water) that could occur during the ignition phase. The operator monitored the DustTrak PM concentration reading, and the nitrogen flow rate into the diluter was adjusted as needed to keep the reading within the instrument's detection range.

The dilution ratio in Sample B relative to the undiluted stack gas (Sample A) is determined using the two CO₂ concentration readings. Sample A's reading was divided by Sample B's to determine a dilution factor for each ten-second interval. The dilution factor is used to convert the measured PM concentration to the actual PM content of the flue gas. See Equation 3-13 in Section 3.4.2 for the dilution factor calculation.

3.3.4 Experimental operating procedures

3.3.4.1 Pre-run set-up for a test sequence

The pre-run setup was completed before each run. The sampling lines were cleaned using acetone. The HEPA and DustTrak II filters were inspected and replaced if needed. The ash from the previous run was removed and stored for additional analysis. The Horiba PG350 gas analysers were disconnected from every sample and calibration gas line and allowed to complete

the necessary start-up procedure. After the machine warm-up time, the gas analysers were calibrated using the gases outlined in Table 3-2. Calibration was completed once daily after switching the analysers on. The additional equipment, such as the scale, heated lines and conditioning units, were switched on. The ice baths were filled, and the fuel sample was prepared. The extraction fan was switched on. The first two pots of water for the water heating test were prepared.

3.3.4.2 Before ignition

The Horiba gas analysers were connected to the diluted and undiluted sampling lines, A and B. The data loggers were started, and the DustTrak II and the Aquaria pump were switched on. The time was recorded. The dilution gas (N_2) was opened for dilution. Data logging was started, and the apparatus was allowed to record ambient conditions for 5 minutes before ignition.

The stove remained on the load cell permanently and was not moved between experimental runs. The pre-weighed pots and sampling lines are placed on the load cell, which is then tared. The fuel and fuel starters (kindling and woodchips) for the entire test sequence are placed on the load cell. This lets the load cell measure only the fuel burned during a testing sequence, with slight interruptions, as a wood cutting is removed from the balance and placed into the hopper.

3.3.4.3 Ignition

Four of the prepared wood cuttings are placed in the stove's hopper. Using only four pieces allows adequate airflow around the logs during ignition. The logs are placed flat onto the grate. Wood chips soaked (80 g) in paraffin are placed on top of the cuttings, followed by small pieces of hardwood kindling (~100 g) of the same species as used in the test sequence. The paraffin-dosed wood chips were ignited using a long-handle lighter. As soon as a flame was visible, the hopper and the cooking hob above the flames were closed. For test sequences using the oven, the oven flap was in the horizontal position during ignition to allow the establishment of the draught. It was flipped to the vertical position when a plume was formed. The air controller was kept fully open during ignition and the high-power phase. The air controller was adjusted to halfway open at the end of the scheduled high-power phase and again fully closed at the end of the medium-power phase. The first refuelling is done 10 minutes after ignition. Thereafter, refuelling is done at a five-minute interval. Ignition is assumed to be completed 30 minutes after lighting the stove, and the water heating test is then commenced.

3.3.4.4 Water Heating Test Sequence

The water heating test is conducted according to the Heterogeneous Testing Protocol (HTP), using two pots with thermocouples added to the lids of the pots. The pots are filled with ~1.6 L of water before each run. The weights of the empty pots and pots filled with water are recorded before each run.

The lids are kept on the pots to limit the evaporation of the water and to mimic real-world cooking practices, as per the HTP. The pots were immediately weighed at the end of each power phase to check for evaporation losses. Each pot has a 3 mm diameter thermocouple attached through the lid, with the tip positioned 50 mm from the bottom. This ensures consistent measurement of the water temperature throughout the test sequence.

The heating test was conducted in three phases, a high power, medium power and low power phase, according to the Heterogeneous Testing Protocol (Robinson *et al.*, 2010). The phases are regulated by changing the stove's air supply while maintaining a constant fuel feed rate.¹ The first phase of the testing sequence begins with the stove at ambient temperature, heating water to 80 °C. Once the water reaches 80 °C, it is replaced with room-temperature water, and the test is repeated for the medium power phase. The low-power phase sequence is conducted last by replacing the water at 80 °C with new room-temperature pots. The temperature is measured in both pots for multi-pot stoves, but only the primary pot must reach 80 °C.

The water heating test is conducted in Potchefstroom at an altitude of 1340 m. A change in altitude could affect the test due to lower water boiling points at higher elevations. Using the stove in Limpopo as intended could deliver different thermal efficiency results.

3.3.4.5 Stove run and fuel feed rate

The water heating test commences 30 minutes after ignition. A complete experimental sequence lasted for 90 minutes. The duration of each power phase was not based on time but on the water temperature, as explained in Section 3.3.4.4, as per the HTP. The duration of each phase was different and dependent on the fuel species used. Once the test's third phase was completed, the pots were left on the stove until the end of the sequence, often reaching boiling point. A volume-based fuel feed rate of one fuel piece of the specified geometry (Section 3.2) was added every five minutes to maintain uniformity across repeated test sequences. Only one log at a time was added, as adding multiple logs simultaneously smothered the fire. The constant fuel feed rate was maintained until the end of the third low-power phase of the HTP, whereafter, the stove was allowed to burn for 90 minutes. Refuelling is stopped after the last phase of the testing protocol since this allows three pots of water to reach boiling point and provides sufficient time for cooking in real-life applications. In most cases, refuelling was halted after 65 minutes since the phases were completed by then for all species. The PM reading was monitored, and the dilution gas was adjusted as required.

¹ Alternate techniques for regulating stoves include fuel feed rate rather than limiting air flow. Fuel feed rate regulation is necessary for open fires and stoves with large open refuelling ports.

3.3.4.6 Shutdown

The sequence was terminated at 90 minutes by switching off the pumps, gas flows and recording instruments. After switching off the measuring instruments, the remaining fuel was allowed to burn out. The data were downloaded and analysed. After the stove cooled, the ash and residual fuel, if any, were removed, and the hopper cleared in preparation for subsequent tests.

3.4 Data processing: Quantifying thermal and emission performance

Based on the Heterogeneous Testing Protocol, the calculations were used with a mass balance to determine the emission and thermal parameters.

3.4.1 Thermal performance

The continuously measured mass data is first used to determine burn rates within the stove. Any abrupt fluctuations in the mass data are manually smoothed by determining the cause of the fluctuation, specifically the disturbances caused by replacing the pots or transferring a fuel piece from the fuel tray into the fuel hopper. Moving averages are used for further refinement of the mass data (Annexure D). The calculations are done on an ash-free basis.

The **lower heating value** (LHV) is determined according to Equation 3-5 (Ogunjuyigbe *et al.*, 2017).

$$LHV = CV_f - H_v(x_{H_2O} + 9x_H) \quad (3-5)$$

where LHV $\left[\frac{MJ}{kg}\right]$ is the lower heating value of the fuel, $CV_f \left[\frac{MJ}{kg}\right]$ is the higher heating value of the fuel, H_v is the heat of vaporisation of water $\left(2.24 \left[\frac{MJ}{kg}\right]\right)$, and x_{H_2O} and x_H are the wood species' moisture (from proximate analysis) and hydrogen fractions (from ultimate analysis).

The **firepower** is determined using Equation 3-6.

$$P = \frac{m_{T,f} \cdot (LHV)}{t_T} \quad (3-6)$$

where P is the firepower [kW], $m_{T,f}$ [g] is the total mass of fuel burnt and t_t [min] is the total time of the test run.

Since the Flamingo™ stove is primarily a cooking and not space heating appliance, the only thermal performance parameter determined is the thermal efficiency. The water heating test sequence is used for this determination.

The **thermal efficiency** is determined using Equation 3-7.

$$\eta_{thermal} = \left(\frac{m_w \cdot C_{p_w} \cdot \Delta T_t}{\Delta m_f \cdot LHV} \right) \times 100 \quad (3-7)$$

where $\eta_{thermal}$ is the thermal efficiency [%], m_w is the mass of water in the pots [g], C_{p_w} is the specific heat capacity of water at 4.2 $\left[\frac{J}{g \cdot ^\circ C} \right]$ and ΔT_t is the change in the water temperature ($^\circ C$) from room temperature to $\sim 80^\circ C$, during an elapsed time t . Δm_f [g] is the fuel mass loss during the interval t .

Lastly, the **specific fuel consumption (SFC)** is determined according to Equation 3-8. The SFC determines the fuel needed to heat a specific amount of water.

$$SFC = \frac{m_{T,f}}{m_w} \quad (3-8)$$

3.4.2 Emission performance

Emission factors characterise the emission performance of the stove. Emission factors are presented per energy released (Bhattacharya, Albina & Abdul Salam, 2002; International Organization for Standardization, 2018a). The emission factors are determined on a dry fuel basis.

A key feature of the HTP is the calculation and use of the fuel burn rate, which requires precise measurement of the mass of the fuel as it is burned, regardless of how small the change is. The **fuel burn rate**, the rate at which the fuel is consumed during combustion, is determined using Equation 3-9. Based on the five-minute refuelling intervals, the fuel feed rate is determined by Equation 3-10.

$$\dot{m}_{burn} = \frac{m_f - m_{f+5}}{t_{f+5} - t_f} \quad (3-9)$$

$$\dot{m}_{feed} = \frac{\bar{m}_c}{t_{interval}} \quad (3-10)$$

where $\dot{m}_{burn} \left[\frac{g}{min} \right]$ is the burn rate of the fuel, m_f [g] is the mass of the fuel at a specific time and, t_f [min] is the corresponding time during the test sequence. $\dot{m}_{feed} \left[\frac{g}{min} \right]$, is the mass feed rate of the wood cuttings during refuelling, $\bar{m}_c$ [g] is the mean mass of one wood cutting and $t_{interval}$ [min] the minute interval used for refuelling.

The Horiba gas analysers report NO_x, SO₂ and CO concentration values in ppm and CO₂ and O₂ in vol%. The concentration values are converted to a fraction for calculation purposes.

The flue gas flow rate, which is needed to determine emission factors, is not measured in the existing rig. It is necessary to determine the molar flow rate of the flue gas in an indirect manner by utilising a carbon balance. An example calculation is demonstrated in Annexure D.

Firstly, the **mass flow rate** of only carbon is determined. The change in mass of the fuel, $\dot{m}_{burn} \left[\frac{g}{min} \right]$ is determined and used in Equation 3-11.

$$\dot{m}_{c,afb} = \dot{m}_{burn} \cdot x_{c,afb} \quad (3-11)$$

where $\dot{m}_{c,afb}$ is the mass flow rate of pure carbon. The carbon percentage ($x_{c,afb}$) is taken from the fuel ultimate analysis results. The **molar flow rate** is determined as shown in Equation 3-12.

$$\dot{n}_{carbon} = \frac{\dot{m}_{c,afb}}{MW_{carbon}} \quad (3-12)$$

where $\dot{n}_{carbon} \left[\frac{mol}{min} \right]$ is the molar flow rate of carbon, and MW_{carbon} is the molecular weight $\left[\frac{g}{mol} \right]$ of carbon. The total mass flow rate of the flue gas is determined from Equation 3-13.

$$\dot{n}_{flue\ gas,\ wet} = \frac{\dot{n}_{carbon}}{(y_{CO} + y_{CO_2})(1 - y_{H_2O})} \quad (3-13)$$

where $\dot{n}_{flue\ gas} \left[\frac{mol}{min} \right]$ is the molar flow rate of the flue gas and y_{CO} , y_{CO_2} are the molar gas fractions of CO and CO₂, which are measured on a dry basis, and y_{H_2O} is the water fraction in the flue gas. The water fraction converts the dry flue gas measurements to a wet basis. Refer to Annexure C, Figure C-1, for the details on the calculation of the water fraction.

The **molar flow rate** of each component is determined by Equation 3-14, using Equation 3-13 to simplify and eliminate the use of the water fraction in the emission factor calculation.

$$\dot{n}_i = \dot{n}_{flue\ gas,\ wet} \cdot y_i \cdot (1 - y_{H_2O}) = \frac{\dot{n}_{carbon}}{(y_{CO} + y_{CO_2})} \cdot y_i \quad (3-14)$$

where $\dot{n}_i \left[\frac{mol}{min} \right]$ and y_i are each component's molar flow rate and gas fraction (where i represents CO, CO₂, SO₂, and NO_x). The molar flow rate is also converted to a wet basis by use of the water fraction – this eliminates the use of it in Equation 3-13, which results in the molar flow rate on a dry basis.

The mass flow rate of each component is determined (Equation 3-15).

$$\dot{m}_i = \dot{n}_i \cdot MW_i \quad (3-15)$$

where $\dot{m}_i \left[\frac{g}{min} \right]$ is the mass flow rate of each component (where i represents CO, CO₂, SO₂, and NO_x).

The **emission factors** for each component are determined by Equation 3-16.

$$EF_i = \frac{\int_0^t \dot{m}_i}{CV \cdot m_{T,f}} \quad (3-16)$$

where $EF_i \left[\frac{g}{MJ} \right]$ is the emission factor determined by integrating the mass flow rate throughout the test and dividing by the calorific value and the mass of the total fuel burnt.

The **dilution factors** for each recording time interval (10-s) are determined using the CO₂ concentrations from the diluted and undiluted streams (Equation 3-17). The CO₂ fraction of Horiba A is divided by the concentration of Horiba B.

$$DF = \frac{y_{CO_2,A}}{y_{CO_2,B}} \quad (3-17)$$

where DF is the dilution factor and $y_{CO_2,A}$ and $y_{CO_2,B}$ are the CO₂ fractions from streams A and B, respectively.

The emission factor for particulate matter is determined by first calculating the flue gas flow rate (Equation 3-18).

$$v_{flue\ gas} = \dot{n}_{flue\ gas} \cdot \frac{R \cdot T_{analyser}}{P_{atm}} \quad (3-18)$$

where $v_{flue\ gas} \left[\frac{m^3}{min} \right]$ is the volumetric flow rate, R is the gas constant $[8.314 \frac{Pa \cdot m^3}{mol \cdot K}]$, $T_{analyser}$ [K] is the temperature of the analyser, where the PM is measured and P_{atm} [86500 Pa] is the atmospheric pressure in Potchefstroom.

The actual PM concentration and, ultimately, the mass flow rate of PM are determined by multiplying the DustTrak PM readings by the dilution factors and flow rate for each time interval (Equation 3-19)

$$\dot{m}_{PM} = v_{flue\ gas} \cdot PM_{measured} \cdot DF \quad (3-19)$$

where $\dot{m}_{PM} \left[\frac{g}{min} \right]$ is the mass rate of the PM.

The integral of the mass flow rate is determined and used to determine the emission factor $\left[\frac{g}{MJ}\right]$ (Equation 3-20).

$$EF_{PM} = \frac{\int_0^t \dot{m}_{PM}}{CV \cdot m_{T,f}} \quad (3-20)$$

The described calculation method is validated in Annexure D as a mass balance over test sequences. An example calculation is also included. **Error! Reference source not found.** shows the recovery rate obtained from this mass balance.

Table 3-6: Recovery rate observed using the carbon balance calculation method.

Species	Recovery (%) (g/100 g)		
	C	N	S
Sickle Bush	102	21	66
Mopane	99	17	75
Leadwood	98	23	38
Black Wattle	96	4	67

For the four species, it is seen that most of the carbon is converted to either CO or CO₂ and insignificantly to other carbon-containing species, such as CH₄. This validates the calculation method since the assumption is that the carbon is recovered in either CO or CO₂. The recovery of sulphur and nitrogen is low, showing that the S and N are lost to other compounds than NO_x and SO₂ as measured. Only NO_x and SO₂ are measured, with no indication regarding the conversion of nitrogen to N₂ or sulphur to H₂S or other sulphur compounds.

3.5 Quality control and data validation

Measures were implemented to minimise operator and instrumental variations in the results. The experimental procedure outlined above was used as a standard operating procedure (SOP), which was determined and written from the standard HTP. Further additions to the protocol, such as the refuelling, were determined from commissioning and stove burn-in. The same procedure was used for each run, including the same ignition procedure and standard start and shut-down procedures.

The instrumentation was cleaned and calibrated before each run. The sample lines were cleaned using acetone and compressed air, and the filters were replaced when necessary. The gas analysers and PM monitor were calibrated daily after switching the equipment on and completing the machine's warm-up. The DustTrak PM monitor was set to ZERO CAL and FLOW CAL and calibrated according to the on-screen instructions. To calibrate the Horiba gas analysers, the gas

ranges were first set according to Table 3-5. The values in the cylinders of the gases should match this set of values. The values of ZERO and SPAN were then recorded. Under the CAL setting, all the gas values were set to zero. The nitrogen gas line was connected to the sample line on the analyser. Gas concentrations were left to stabilise before executing the ZERO option. The new zero values were recorded. The nitrogen flow was then closed. The CO line was connected, all the gases were set to blank except for CO. CO flow was opened, and the CO concentration was recorded before SPAN calibration was executed. The same procedure was repeated for the different gases. The calibration line was then isolated.

The equipment, including the gas analysers and conditioning units, was serviced before the commencement of the experimental schedule and when operational issues arose. The quality assurance procedures described were established from previous studies at the North-West University, and the finer details were established during the commissioning experiments as described in Annexure A.

The experimental uncertainty was determined using a 95% confidence interval using Equation 3-21. Details on this are found in Annexure E.

$$CI = \bar{x} \pm t\left(\frac{\alpha}{2}, n - 1\right) \frac{S}{\sqrt{n}} \quad (3-21)$$

where $\bar{x}$ is the mean value, $t\left(\frac{\alpha}{2}, n - 1\right)$ is the quantile from the t-distribution at a significance level of α (0.05 for 95% CI), S is the standard deviation of a sample and n is the number of runs. The 95% confidence interval was sufficient, with the interval narrow enough, with low variability and low standard deviation.

3.6 Experimental schedule

After the initial commissioning tests, the stove was tested using each of the four fuel species. The effect of the novel feature of the stove, the oven, was investigated by conducting runs with and without the oven in use, meaning with the flap in the horizontal or the vertical position for each wood species. Eight formal experimental runs are planned. The tests are repeated in triplicate, resulting in 24 experimental sequences. Table 3-7 provides a summary of each experiment and the experimental parameters.

Table 3-7: Experimental sequences and variables.

1	Sickle Bush	3	Mopane	5	Leadwood	7	Black Wattle
	Flap: Horizontal		Flap: Horizontal		Flap: Horizontal		Flap: Horizontal
2	Sickle Bush	4	Mopane	6	Leadwood	8	Black Wattle
	Flap: Vertical		Flap: Vertical		Flap: Vertical		Flap: Vertical

3.7 Ethics clearance

The NWU Ethics Committee gave ethical clearance to this project. The committee declared the study 'no risk' and assigned an ethics number NWU-00488-24-A3.

CHAPTER 4 RESULTS AND DISCUSSION

Sections 4.1 and 4.2 discuss the wood selection, sourcing and characterisation results. In Section 4.3, general observations made from the test sequences, as well as the stove's operation, are discussed. Temperature profiles and the composition of the flue gas are discussed. Furthermore, the emission and thermal performance are discussed in Sections 4.4 and 4.5, respectively. In Section 4.3 to Section 4.5, the findings presented are for sequences where the oven was not in use. Lastly, the effect of using the oven is discussed in Section 4.6 through comparison with the results discussed in the first three sections. Throughout, the performance of the four selected species will be compared. In this chapter, comparisons with literature are attempted but constrained by the Flamingo™ stove's unique operation and specifications. Standardised performance parameters, such as efficiency and emission factors, are compared where possible.

4.1 Wood selection and sourcing

The chosen four species are Sickie Bush (*Dichrostachys cinerea*), Mopane (*Colophospermum mopane*), Leadwood (*Combretum imberbe*) and Black Wattle (*Acacia mearnsii*). The four species are found in the Limpopo Province, but also Mpumalanga, and in some cases in Gauteng and Kwa-Zulu Natal (Aubrey, 2004; Cheek, 2009; Mtsweni, 2006). Due to its prominence in communities nationwide, Black Wattle (*Acacia mearnsii*) was added to the study as a reference fuel. Black wattle is an appropriate choice of firewood since it is an invasive species (originally from Australia) and has infested Limpopo, Mpumalanga, the Western & Eastern Cape, Gauteng and Kwa-Zulu Natal (Invasives South Africa, 2024).

4.2 Wood characterisation results

The results obtained from the above characterisation analyses, proximate, CV, ultimate, fibre and density analysis are discussed.

4.2.1 Proximate analysis

Table 4-1 reports the proximate analysis results of the four selected wood species.

Table 4-1: Proximate and calorific value analysis results.

Proximate analysis (air-dried basis) (wt%)						
	% Moisture	% Ash	% Volatile matter	% Fixed carbon*	Fuel ratio**	CV (MJ/kg)
Sickle Bush	6.7	2.9	70.8	19.6	0.28	19.1
Mopane	7.9	2.3	68.1	21.7	0.32	18.9
Leadwood	7.9	9.2	64.5	18.4	0.29	15.9
Black Wattle	8.7	0.9	74.8	15.6	0.21	18.7

*By difference. ** Ratio of fixed carbon to volatile matter.

Vassilev *et al.* (2010) reviewed the proximate analysis of 28 woody biomass samples, determining the ranges of ash yield (0.1–16.5%), volatile matter (69.5–86.3%) and fixed carbon (12.3–26.3%) contents. The results of the four species in Table 4-1 fall within these typical ranges for wood. The ash yield of Sickie Bush, 2.9%, aligns well with the findings of Pedroso and Martin (2011) and Rubio-González *et al.* (2021), who reported a range between 2 and 4%. Similarly, the reported values of volatile matter and fixed carbon for the species range between 72–78% and 19–23%, respectively, which also coincides with the values reported in Table 4-1 (Pedroso & Martin, 2011; Rubio-González *et al.*, 2021).

Black Wattle presented a particularly low ash value, corresponding to the ash values of 0.5% reported by Makonese and Bradnum (2018). The volatile matter and fixed carbon for Black Wattle also correspond to the reported values of 64 and 30%, respectively (Bradnum & Makonese, 2018). Mopane and Leadwood have less published data on their physicochemical properties, but the results obtained here are in the typical range for wood. Leadwood shows a relatively high ash content, which correlates with what Tietema *et al.* (1991) reported. According to Tietema *et al.* (1991) Mopane and Leadwood have ash yields of 3.8% and 14.2%, respectively, which correlate well with the values determined.

The calorific values reported in Table 3-2 are also in a similar range for woody biomass. Telmo and Lousada (2011) determined the CV values of different species of wood pellets and reported a range between 17.6–20.8 MJ/kg, which coincides with the ranges of CV values for the four species. Pedroso and Martin (2011) reported a CV value of 19.8 MJ/kg for Sickie Bush, which is in the same order of magnitude as the value shown here. Leadwood reported a low CV value, which is attributed to the species' high ash content. (Amriansyah & Sihombing, 2021).

4.2.2 Ultimate analysis

Table 4-2 shows the results from the ultimate analysis.

Table 4-2: Ultimate analysis results.

Ultimate analysis (dry, ash-free basis) (wt%)					
	% C	% H	% N	% S	% O*
Sickie Bush	52.4	6.7	0.5	0.08	40.2
Mopane	52.8	6.7	0.4	0.08	40.0
Leadwood	51.4	6.2	0.3	0.08	42.0
Black Wattle	52.0	5.5	1.9	0.08	40.5

*By difference

The review by Vassilev *et al.* (2010) of 28 wood samples described a range for carbon content between 48.7–57.0%, hydrogen content of 32.0–45.3%, nitrogen content of 0.1–0.7%, sulphur content between 0.01–0.42% and lastly for oxygen content between 32.0–45.3%. The mean sulphur content was described as 0.08%, which is similar to the values found for each of the four species in Table 4-2 (Vassilev *et al.*, 2010). The values shown in Table 4-2 fall within these typical ranges for wood. The sulphur contents of the four species are similar to the values reported by Tariq *et al.* (1994) of between 0.01 and 0.07% for different wood species.

The ultimate analysis results in Table 3-3 are comparable to values found in the literature. Sickle Bush values are similar to those reported by Pedroso and Martin (2011), who reported 49.3% carbon, 5.3% hydrogen and 42.5% oxygen content (Pedroso & Martin, 2011). Mopane sapwood showed a carbon content of 50%, hydrogen of 6.4% and oxygen of 43.5% (Tietema *et al.*, 1991). Leadwood exhibits carbon, hydrogen and oxygen contents of 51.4%, 5.8% and 42.5%, respectively (Tietema *et al.*, 1991). A noteworthy value is Black Wattle's high nitrogen content (Table 3-3). This is supported by the values reported by Makonese and Bradnum (2018), who found a nitrogen content of 1.5%, carbon of 49.2% and hydrogen of 6.5%.

A Van Krevelen diagram is illustrated (Figure 4-1) from the ultimate analysis results. According to this, the wood species fit into the section of the diagram where biomass is usually found (Khan *et al.*, 2022). An overlap between Sickle Bush and Mopane is observed. Leadwood is the outlier due to its high oxygen content and high O:C ratio.

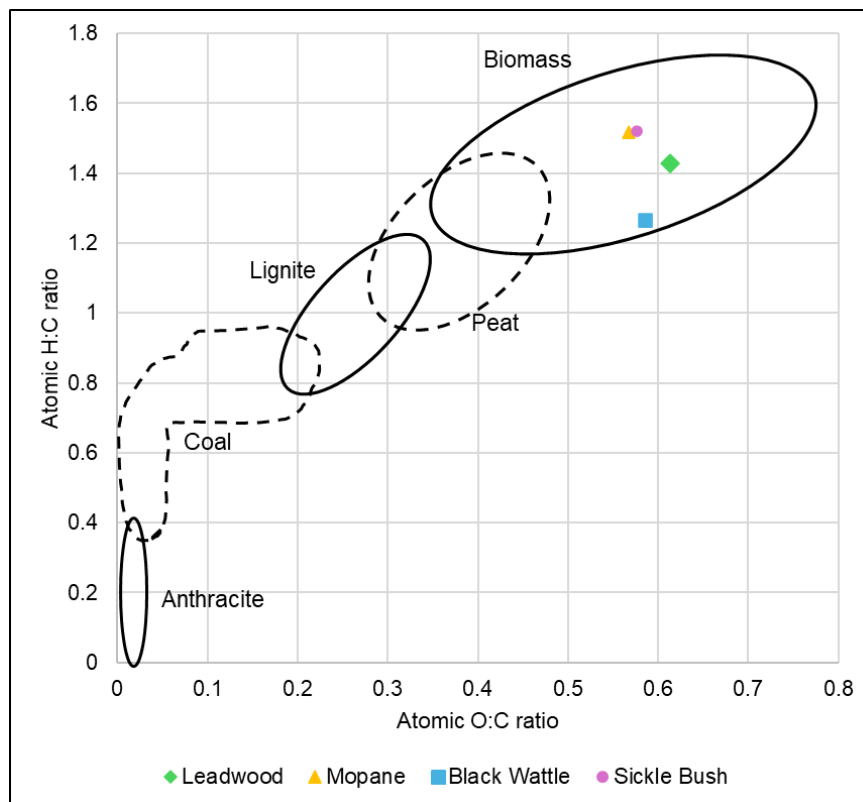


Figure 4-1: Van Krevelen Diagram of the four species.

4.2.3 Wood density

Table 4-3 indicates the wood densities determined. Experimental values for the density determination are shown in Table B-1 (Annexure B).

Table 4-3: Density of the wood species.

Density (kg/m ³)	
Sickle Bush	1 307 ± 279
Mopane	1 415 ± 153
Leadwood	1 466 ± 138
Black Wattle	993 ± 63

The highest-density species were Leadwood and Mopane, and the lowest was Black Wattle. The density and measurements required for its determination showed a high variability across different cuttings. This is linked to the homogeneity of the various wood samples. Although the cuttings are of similar volume, the composition differs since some pieces contain sapwood, some contain heartwood, and others combine the two. Black Wattle, with the lowest deviation, is assumed to be the most homogeneous sample, while Sickle Bush is the least homogeneous sample.

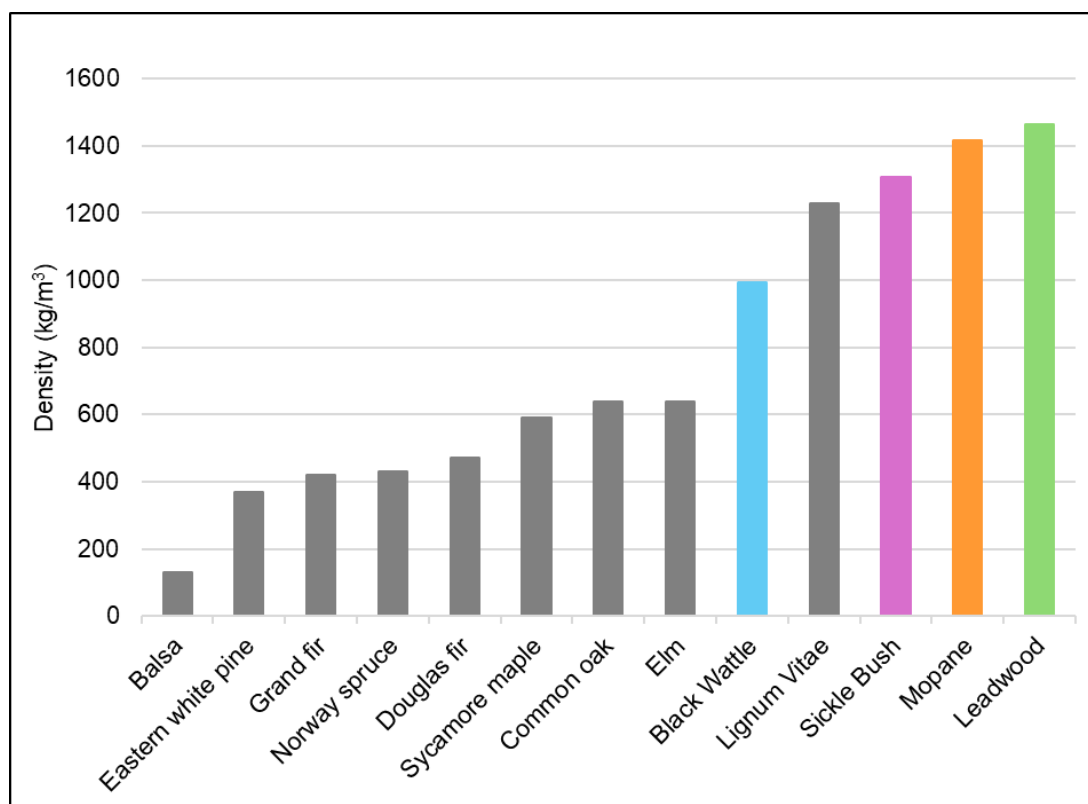


Figure 4-2: Wood density comparison. Adapted from (Niemz et al., 2023).

The species are dense compared to other wood species (Figure 4-2). From the high densities, it is seen that the four species can be classified as hardwoods.

4.2.4 Fibre analysis

The results from the fibre analysis are presented in Table 4-4.

Table 4-4: Fibre analysis results.

Fibre analysis (dry, ash, extractive free) (wt%)			
	Hemicellulose	Cellulose	Lignin
Sickle Bush	18.0	51.5	30.4
Mopane	15.5	50.1	34.4
Leadwood	29.0	36.6	34.4
Black Wattle	31.3	51.0	17.7

It has been reported that hardwoods have cellulose, hemicellulose and lignin contents of 40-55%, 15-40% and 18-25%, respectively (Ahmad *et al.*, 2020; Betts *et al.*, 1991; Malherbe & Cloete, 2002). Softwoods have similar cellulose contents, with a value between 40-55%, while they exhibit a higher hemicellulose content (25-35%) and a higher lignin content of 25-35% (Ahmad *et al.*, 2020; Betts *et al.*, 1991; Malherbe & Cloete, 2002). From this, it is seen that the four species fall within the typical ranges for wood. The higher lignin content of the three species is unforeseen since the woods are classified as hardwoods – only Black Wattle falls within the reported range for the lignin content of hardwoods.

A correlation is observed between the lignin content and the density of wood (Figure 4-3), through linear regression. Higher lignin content correlates with higher density, which is also supported by the findings of Maiti *et al.* (2016). The low lignin content of Black Wattle is likely the cause of the low density observed (Figure 4-3). The two species with similar densities, Leadwood and Mopane, show similar lignin contents.

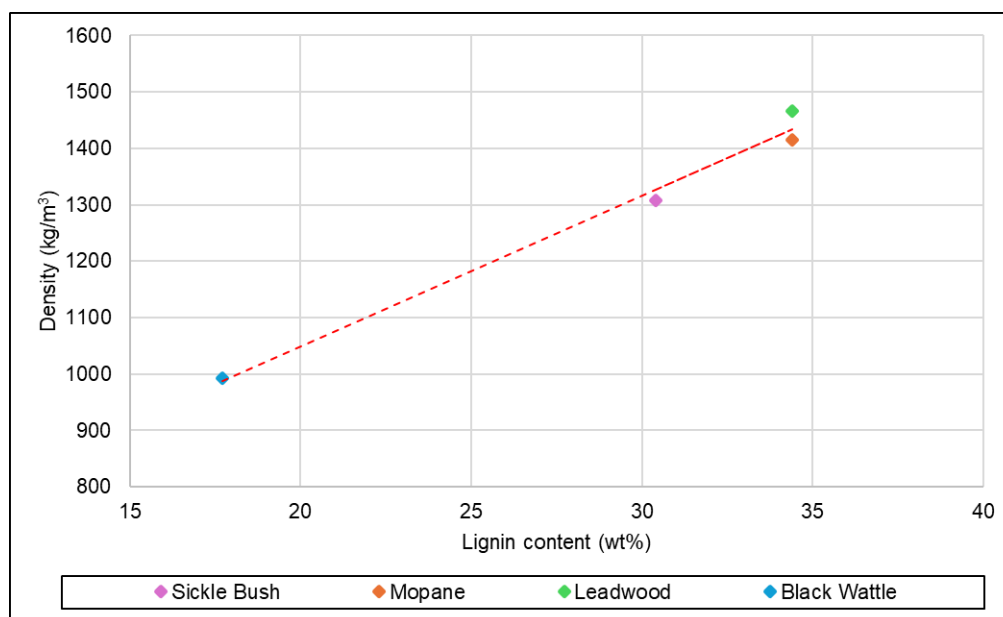


Figure 4-3: Relationship between the lignin content and density of each species.

4.2.5 Summary

Table 4-5 summarises the results obtained for the characterisation of the four fuelwood species.

Table 4-5: Summary of the physicochemical properties of the four species.

	Sickle Bush	Mopane	Leadwood	Black Wattle
Proximate analysis (air-dried basis) (wt%)				
Moisture	6.7	7.9	7.9	8.7
Ash	2.9	2.3	9.2	0.9
Volatile matter	70.8	68.1	64.5	74.8
Fixed carbon	19.6	21.7	18.4	15.6
Fixed carbon to volatile matter ratio	0.28	0.32	0.29	0.21
Calorific Value (air-dried basis) (MJ/kg)				
CV	19.1	18.9	15.9	18.7
Ultimate analysis (dry, ash-free basis) (%)				
C	52.4	52.8	51.4	52.0
H	6.7	6.7	6.2	5.5
N	0.5	0.4	0.3	1.9
S	0.08	0.08	0.08	0.08
O	40.2	40.0	42.0	40.5
Fibre analysis (dry, ash, extractive free) (%)				
Hemicellulose	18.0	15.5	29.0	31.3
Cellulose	51.5	50.1	36.6	51.0
Lignin	30.4	34.4	34.4	17.7
Density (kg/m³)				
Density	1 307 ± 279	1 415 ± 153	1 466 ± 138	993 ± 63

The four species show similar values for physicochemical properties as typically reported for wood, with a few exceptions. The high ash yield of Leadwood is not typically seen in wood, which results in Leadwood having the lowest CV value. Black Wattle showed an ash yield lower than typically seen in wood. Black Wattle and Sickle Bush demonstrated the lowest fixed carbon to volatile matter ratio, while Mopane and Leadwood showed higher ones.

The ultimate analysis results are within the typical ranges. The four species showed similar values, except for Leadwood, which showed the lowest carbon and highest oxygen content. The fibre analysis results are in typical ranges, but Black Wattle showed a lower lignin content than typically seen. Lastly, the species show high densities compared to other wood species, with Black Wattle demonstrating the lowest density between the four species. Nevertheless, their high densities classify all four species as hardwoods.

4.3 General observations

4.3.1 Fuel consumption, burn rates and power output

Figure 4-4 shows the normalised fuel consumption of each wood species. Only one of the three test runs is shown in the figure. Leadwood is observed to be the slowest burning, alongside Mopane, while Black Wattle and Sickie Bush are the two fastest burning species. Leadwood showed the lowest conversion, reaching a conversion of 0.64 after the 90-minute test sequence. Refuelling intervals of 5 minutes are indicated, but no significant changes are observed due to refuelling. This could be attributed to the short interval between refuelling.

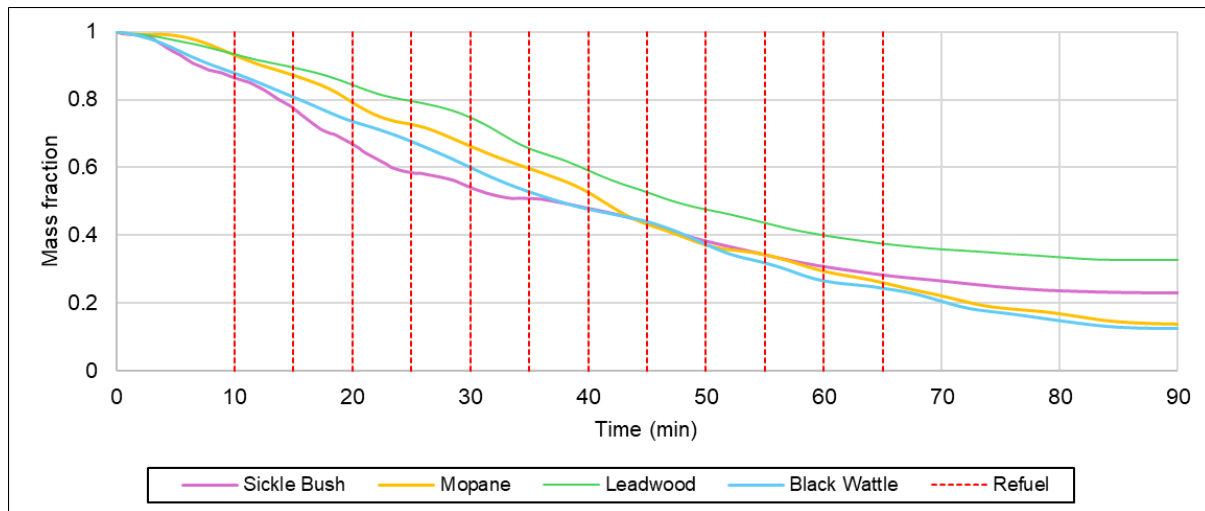


Figure 4-4: Fuel consumptions of four wood species over the 90-minute test with 5-minute refuelling intervals are shown.

Table 4-5 shows the burn rates and the firepower, density and feed rate achieved from each wood species for three experimental sequences.

Table 4-6: The burn rates, firepower, density and feed rate from each wood species during a 90-minute test sequence.

		Sickle Bush	Mopane	Leadwood	Black Wattle
Density	kg/m ³	1 307 ± 279	1 415 ± 153	1 466 ± 138	993 ± 63
Feed rate	g/min	14.8 ± 1.90	13.0 ± 2.0	20.6 ± 2.10	13.5 ± 2.20
Burn rate	g/min	14.2 ± 3.0	10.2 ± 2.5	10.2 ± 2.80	11.1 ± 4.30
Rel. burn rate ¹	Ratio	0.96 ± 0.18	0.78 ± 0.2	0.49 ± 0.07	0.82 ± 0.19
Firepower	kW	4.1 ± 1.80	3.1 ± 0.70	2.8 ± 0.80	3.1 ± 1.10

¹ Burn rate divided by the feed rate. Also, conversion after 90 minutes.

Sickle Bush is the fastest-burning species, while Leadwood burns the slowest. Sickle Bush showed the highest power output and Leadwood the lowest. There is an evident correlation between the burning rate and density since higher densities result in lower burning rates. The slower-burning species, Mopane and Leadwood, showed the highest densities. Since a relationship exists between the density and lignin (Figure 4-3), the lignin content also contributes to the lower burn rates. Lignin is the least reactive of the three wood constituents, and high lignin content is found to delay or inhibit combustion phases, such as pyrolysis, and hence cause higher burn rates (Gani & Naruse, 2007; Yan *et al.*, 2019). The rate at which the wood burns can benefit the cook – faster-burning species for higher heat or longer-burning species to increase the cooking duration.

Refuelling was conducted on a volume basis, as the wood cuttings differed in mass. Due to the slight differences in the cutting sizes and, consequently, the difference in mass, the mass feed rate was different from species to species. The feed rate, although time-based, can also be calculated and related to the mass of the cuttings of each species, with the highest feed rate of the heaviest species, Leadwood. This is done to compare to the mass-based burn rate. Leadwood is also the densest species due to its high mass. Mopane showed a high density but a low feed rate. The Mopane cuttings were smaller in volume and, consequently, mass, which is proportional in the density calculation. The smaller mass influences the calculation of the feed rate – since Leadwood weighs twice that of Mopane, the feed rate is double despite similar densities. The Sickle Bush and Black Wattle were the species with an almost equal burn rate and feed rate, as seen by the high relative burn rate in Table 4-6. This was also observed during the experimental sequences since there would be less wood in the combustion chamber when refuelling than for the other two species. Leadwood, the densest wood, showed a low burn rate compared to the high feed rate, resulting in the lowest relative burn rate.

It is expected that Sickle Bush and Black Wattle, due to their higher volatile matter and the consequent lower fixed carbon to volatile matter ratio (Table 4-1) will ignite easily. Mopane and Leadwood will have more stable combustion but are more difficult to ignite due to their higher fixed carbon content and lower volatile matter. This is confirmed by the burning of Sickle Bush and Black Wattle being faster, while Mopane and Leadwood burn slower, as shown in Table 4-6.

Makonese and Bradnum (2018) tested small hopper stoves using Black Wattle wood, in cuttings of 400 mm in length and the HTP, as used in this study. The stoves tested were 127 and 101 mm in diameter with varying secondary air inlets. They reported firepower between 2.1 and 4.2 kW between the tested six stoves. For the small hopper stove with two secondary air inlets, the closest configuration to the Flamingo™, a firepower of 2.5 kW was reported (Makonese & Bradnum, 2018). This is close to the 2.8 kW firepower achieved using Black Wattle in the Flamingo™ stove. The higher power outputs reported were exhibited by the larger stoves, which

require a higher fuel mass. Makonese and Bradnum (2018) reported a burn rate of 8.5-12 g/min, similar to what is achieved on the Flamingo™ stove.

For an improved cookstove, with a chamber height of 180, 225 or 370 mm, using sawdust briquettes, a burn rate and power output of 26.7 g/min and 7.8 kW were reported, respectively (Obi *et al.*, 2020). Both values are higher than those achieved by any wood species tested. Larger sizes and higher feed rates could produce higher power output values. The sawdust briquettes used also had a higher CV (33 MJ/kg) and a volatile matter content (90.0 wt%) than the raw wood cuttings, which could lead to higher burn rate values. In a TLUD stove, using wood pellets, a burn rate of 13 g/min and a power output of 4.2 kW were observed, which is in the same range as that shown by the Flamingo™ stove (Sonarkar & Chaurasia, 2019).

The Flamingo™ stove's burn rate and power output are comparable to previous studies using other stove models and other types of fuelwoods, such as pellets. These results confirm that the density and fuel properties affect each species' burn rates and power output.

Continuous refuelling is required when using all four species. A set time of every five minutes was used to compare the fuels. A different refuelling rate could be used in real-world applications, depending on whether the user wants high, medium, or low power. Refuelling could be seen as a hindrance or a safety concern, but this adds a control feature for the user to regulate the stove. Continuous refuelling could deter users from using the stove since higher fuel consumption and running costs could be assumed from continuous refuelling. Although continuous refuelling is necessary, the Flamingo™ stove uses less fuel (~1.2 kg) than traditional stoves to run for 90 minutes.

The figures in this section show one representative run of each species, but the values in the tables take the average of three runs for each species. The raw data graphs and tables are for runs with the oven flap in the horizontal position – the oven was not in use.

Fuel bed temperatures

Figure 4-5 shows the fuel bed temperature during a 90-minute test sequence for each of the four species (thermocouple FB-01 as shown in Figure 3-8).

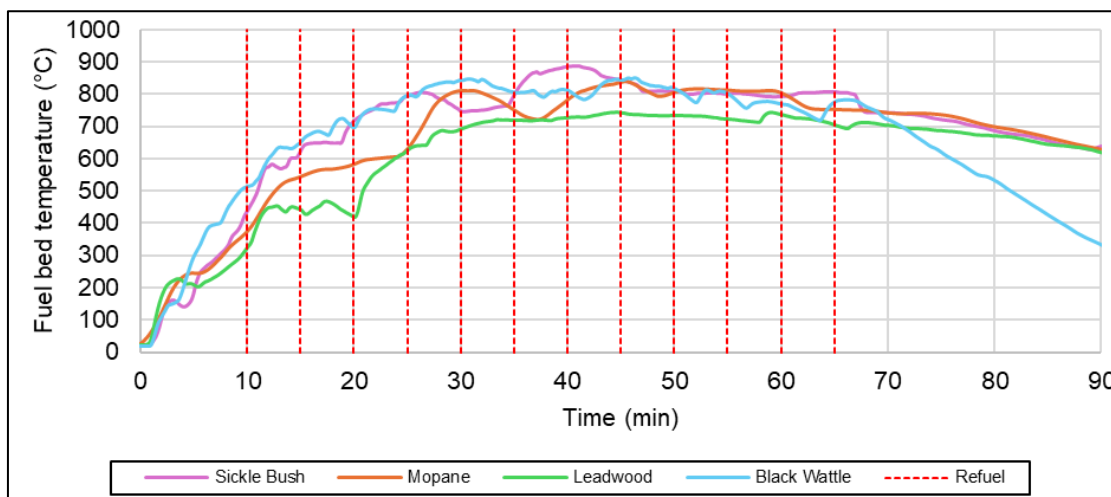


Figure 4-5: Fuel bed temperature for each of the four species.

The quick refuelling interval prevented any abrupt decreases in the fuel bed - refuelling at a 5-minute interval allowed the fuel bed temperature to increase at a relatively constant rate. As seen in Figure 4-5, no sudden increases or decreases are observed with the addition of a fuel cutting. The four species showed a decrease in fuel bed temperature once refuelling was stopped, but Black Wattle showed the quickest temperature drop. This quick decrease is attributed to the low density and the fact that this species achieves the highest conversion (Figure 4-4) once refuelling is completed. The low ash content of Black Wattle could also contribute, the same as the high ash content of Leadwood, which contributes to its longer temperature retention. The relative burn rate for Black Wattle was also high, contributing to this. This decrease proves that refuelling is continuously needed to keep the stove at the correct temperature for cooking.

It is seen that the wood species used affects the maximum fuel bed temperature in the Flamingo™ stove. Sickie Bush demonstrated the highest maximum fuel bed temperature of 897 ± 7 °C, while Leadwood showed the lowest at 755 ± 16 °C. Mopane and Black Wattle showed values of 834 ± 19 °C and 841 ± 49 °C respectively. The four species show a similar increase in temperature during the first 5 minutes of the testing sequence, which coincides with the drying phase of wood during combustion, whereafter the temperature changes at different rates for the different combustion phases. Sickie Bush, the fastest burning species and the species with the highest power output, showed the highest maximum fuel bed temperature. Leadwood, with the lowest power output, showed the lowest maximum fuel bed temperature. Black Wattle demonstrated a high-power output and produced a high fuel bed temperature, which could also be related to the high CV value reported for the species.

The use of a specific species is mainly dependent on the user. Higher temperatures are required for certain foods, while lower temperatures can be used for other purposes. The user can also decide to use specific species to increase or decrease the cooking time by choosing longer or shorter burning species.

Compared to TLUD semi-gasifier cookstoves, using wood pellets, the Flamingo™ stove showed comparable fuel bed temperatures. Tryner *et al.* (2014) reported maximum fuel bed temperatures between 500 and 810 °C, depending on the fuel/stove combination tested. The height of the stove varied between 25 and 64 cm and was filled for each test. In an improved pellet stove, height of 30.5 cm, using biomass waste pellets, a maximum fuel bed temperature of ~990 °C is achieved (Vitoussia *et al.*, 2021). Depending on the species used, the Flamingo™ stove fuel bed temperature compares well to other stove models and fuel types, providing similar values.

Chimney temperature

Figure 4-6 shows the chimney temperatures for each of the four species. These readings were taken by the thermocouple labelled Chimney in Figure 3-8.

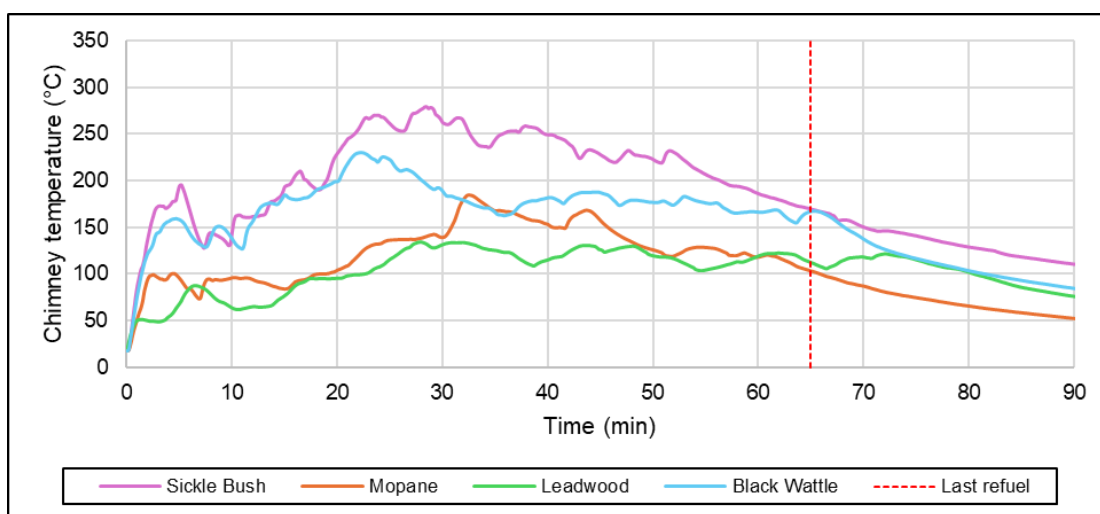


Figure 4-6: Chimney temperature of the four species.

The same trend is observed for the chimney (stack) temperature as for the fuel bed, which is anticipated since a higher fuel bed temperature will result in a higher airflow temperature and, consequently, a higher chimney temperature. Mopane loses heat faster than the other three species once refuelling is stopped. Sickle Bush and Black Wattle showed similar fuel bed temperatures, but the chimney temperatures differed. The differing properties of the two species could be the source of the deviation, including the moisture content and the density. Black Wattle demonstrated a lower density and a high relative burn rate, resulting in lower temperatures. The Black Wattle average volumetric flow rate is also the highest. It could contribute to reporting a lower chimney temperature – higher flow rates result in higher heat transfer rates and a higher loss of heat (Chae & Chung, 2015).

Black Wattle and Sickle Bush had the highest chimney temperatures (215 ± 13 °C and 265 ± 39 °C), while Mopane and Leadwood had the lowest (205 ± 12 °C and 190 ± 12 °C). The high-power output of Sickle Bush results in higher chimney temperatures, while the low-power output results in lower chimney temperatures.

Flame temperature

Figure 4-7 shows the flame temperature directly beneath the first hob achieved by each of the four species. This is measured by thermocouple P-01 in Figure 3-8.

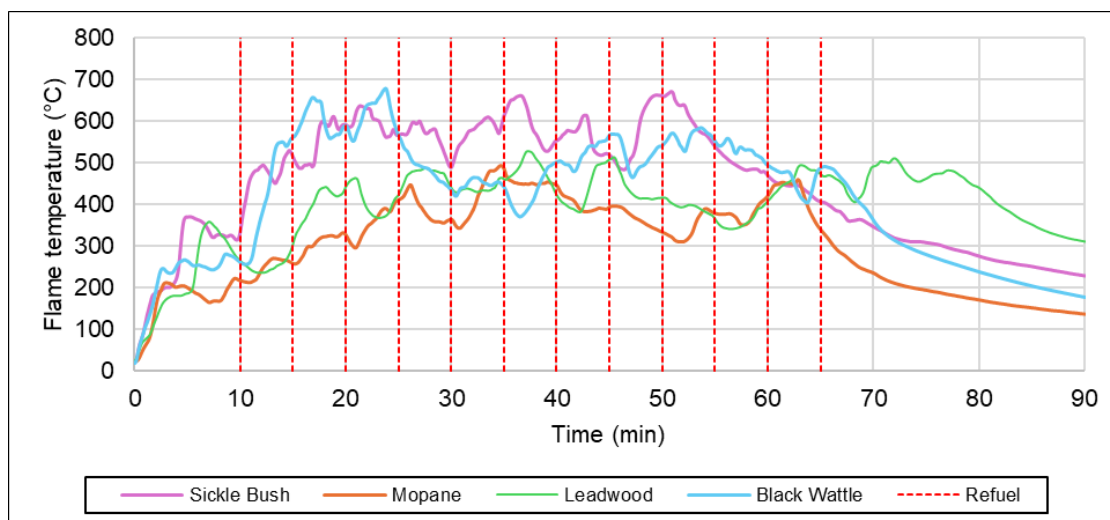


Figure 4-7: Flame temperature of the four species.

The flame temperature increases steadily during the first 5 minutes after ignition, rapidly increasing as the cuttings ignite. The two faster-burning species showed the highest flame temperatures, and Leadwood showed the lowest. Although Leadwood reported lower overall flame temperatures, it maintained elevated temperatures after refuelling was stopped. This could be due to the lower thermal conversion of Leadwood and having the most unburnt wood after 90 minutes. Leadwood had a temperature of 300 °C at the end of the 90-minute test run, while the rest of the species had a temperature between 100 and 200 °C. The flame's temperature is influenced by refuelling, as seen by the increase in temperature after each refuelling event. New wood cuttings are added to the fuel bed and ignited by the smouldering pieces. The new cuttings will undergo flaming combustion, the fast release of volatiles from the new cutting, and thus, the observed increase in the flame temperature after each refuelling event. The four species, Sickie Buhs, Mopane, Leadwood and Black Wattle, have average flame temperatures of 656 ± 34 °C, 540 ± 35 °C, 532 ± 21 °C and 633 ± 31 °C, respectively.

A biomass cookstove, fuelled with corncobs, coconut shells and woodchips, achieved average flame temperatures of 797, 941 and 857 °C, respectively. (Suhartono *et al.*, 2018). A biomass-gas cookstove produced maximum flame temperatures up to ~740 °C for an airflow ratio of 6.29 (Supramono & Inayati, 2013). An airflow ratio of 13.43 showed maximum temperatures below 500 °C, while a low ratio of 2.44 showed maximum temperatures below 400 °C (Supramono & Inayati, 2013). Kshirsagar and Kalamkar (2016) reported on the flame temperatures of stoves using different chimney configurations at different oxygen availabilities. A flame temperature range of 453 to 1082 °C was reported (Kshirsagar & Kalamkar, 2016).

The species produced maximum flame temperatures below 700 °C in the Flamingo™ stove, comparable to previously reported values. The results and previously reported values show that maximum flame temperatures differ from species to species.

4.3.2 Flue gas composition

The flue gas composition is discussed in this section. Each graph shows one representative experimental sequence of each of the four species.

Average volumetric flow rate

Leadwood and Sickie Bush showed similar average volumetric flow rates (0.5 ± 0.0 and 0.4 ± 0.0 m³/min), while Mopane and Black Wattle showed faster flow rates (0.7 ± 0.3 and 0.9 ± 0.6 m³/min). Black Wattle is a fast-burning species and requires more oxygen, resulting in an increased draught. In contrast, Sickie Bush, another fast-burning species, shows lower flow rates. The flow rate is not measured in this rig but calculated theoretically and could also depend on the fuel properties (carbon content) and emission concentrations.

CO₂, CO and O₂ concentrations

Figure 4-8 shows CO₂, O₂ and CO concentrations in the flue gas as produced by each of the four species.

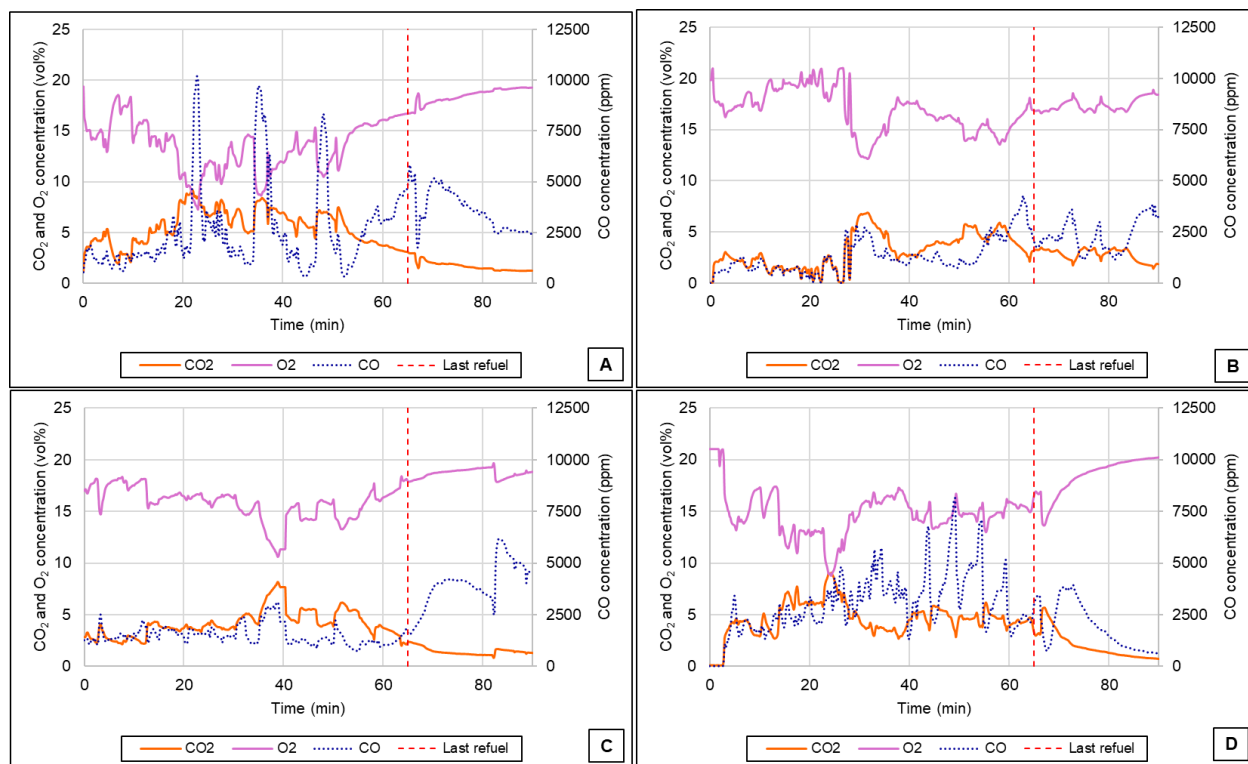


Figure 4-8: CO and CO₂ concentration shown by A) Sickle Bush, B) Mopane, C) Leadwood, and D) Black Wattle.

The CO and CO₂ concentrations have an inverse trend to that of the O₂ concentrations. Chemically, this is due to oxygen being a reactant in the combustion reaction, resulting in the formation of CO and CO₂, depending on the combustion quality. The concentrations of CO₂ and O₂ are inversely related, which implies that the formation of CO₂ is the primary use of oxygen. The sum of the three, at any time during the sequence, is in the range of 16.8 – 21.2%, similar to the ambient O₂ concentration. No apparent effect of refuelling is observed in any of the concentrations of flue gases. This could be attributed to the frequent interval of refuelling, with any peaks or disturbances caused overlapping between refuelling incidences. An increase in the CO concentration is observed after the last refuelling interval due to the decrease in temperature due to fuel depletion. CO forms from a lower heat of formation than CO₂ and is produced at a lower temperature, which is why high stove temperatures are favourable (Bryden *et al.*, 2005).

The two faster-burning species, Sickie Bush and Black Wattle, demonstrated higher concentrations of CO and CO₂ than the two slower-burning species. Sickie Bush and Black Wattle also showed sudden peaks in the CO concentration throughout the test sequence. The sudden increase in CO could be attributed to oxygen depletion and an increase in incomplete combustion, as suggested by the sharp decreases in the O₂ concentration. The depletion of O₂ is attributed to the higher burn rate of Sickie Bush and Black Wattle. Mopane, Figure 4-8B, showed low concentrations of CO and CO₂ compared to the other species. For Leadwood, Figure 4-8C, a more stable CO concentration is observed than for the other species. No peaks are observed in the CO, except after the last refuelling. The concentrations observed in Black Wattle are similar to those reported for Sickie Bush. Inverse CO₂ and O₂ are observed, peaks in the CO around refuelling intervals, and no sharp increase in the CO towards the end of the 90 minutes is seen. The maximum CO₂ concentration of the four species was achieved by Sickie Bush (9.2 vol%), and Mopane reported the lowest maximum CO₂ concentration at 6.8 vol%. Sickie Bush also exhibited the highest maximum CO concentration at 10×10^3 ppm.

Qiu (2013) reported average CO₂ concentrations between 11.3–13 vol% and CO concentrations of 0.1–0.7 vol%, higher than the average concentrations of the four species and the Flamingo™ stove. Unexpected peaks and deviations between runs could be due to the low homogeneity between the samples (Section 3.4.4), but also due to any disturbances in the lab, the airflow or movement of the samples, since combustion of biomass is unpredictable (L'Orange, DeFoort, *et al.*, 2012).

NO_x and SO₂ concentrations

Figure 4-9 shows the concentration of NO_x and SO₂ as produced by each species.

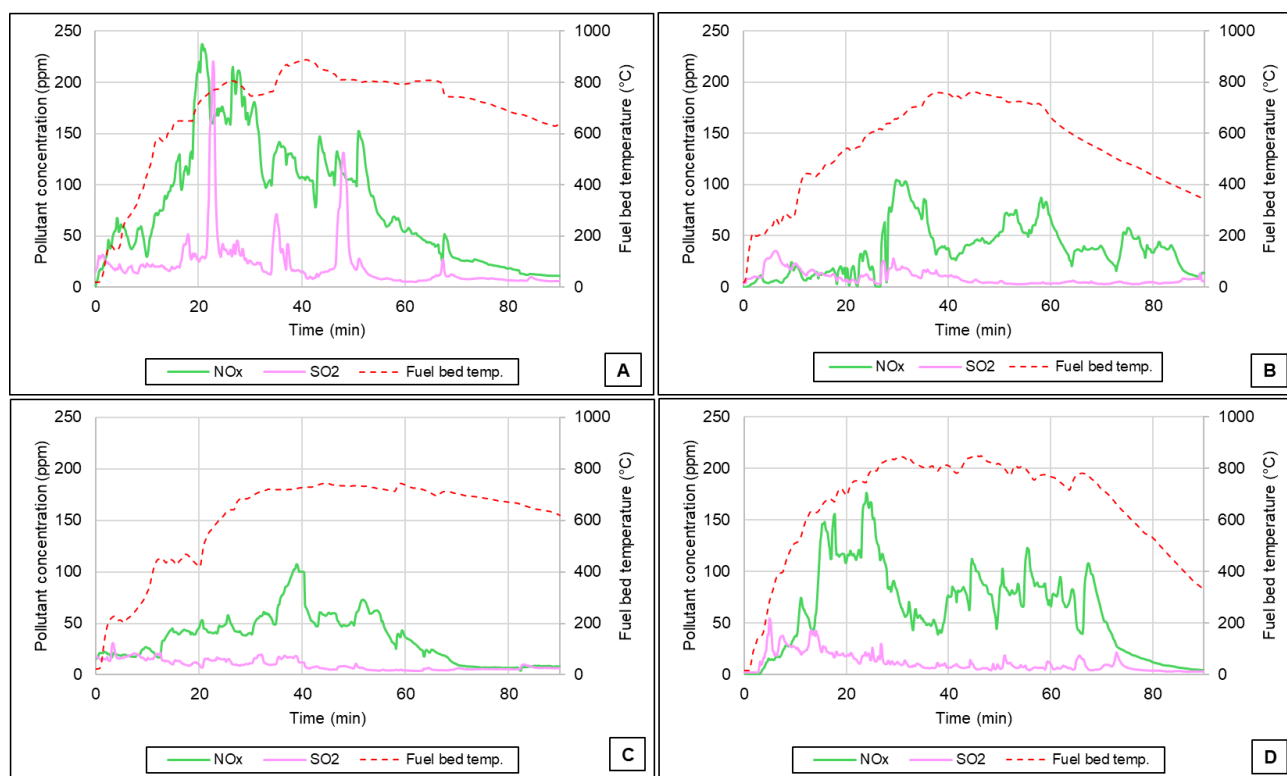


**Figure 4-9: NO_x and SO₂ concentration and fuel bed temperature shown by
A) Sickle Bush, B) Mopane, C) Leadwood and D) Black Wattle.**

The NO_x concentrations observed are higher than the SO₂ concentrations. The formation of NO_x in cookstoves can often be attributed to two factors – the fuel nitrogen content and the combustion temperature (Li *et al.*, 2022). Temperatures in the Flamingo™ stove remain below the threshold temperatures (~1 300 °C) required to form thermal NO_x - a reaction between oxygen and nitrogen in ambient air (Muñoz *et al.*, 2023). A more significant contributing factor should be the nitrogen content in each wood species (fuel NO_x). SO₂ increases with the increase in temperature, as higher temperatures promote SO₂ formation and the influence of the fuel-S content (Wu *et al.*, 2020). Lower temperatures and low oxygen supply could lead to inefficient sulphur oxidation and increase SO₂ formation.

Sickle Bush (Figure 4-9A) showed the highest peaks in both NO_x and SO₂ concentrations, which could be attributed to the species' higher burning rate and higher power output. Black Wattle, the second fastest-burning species, showed the second-highest peak concentrations. Leadwood exhibits stable NO_x and SO₂ formation with fewer peaks during the 90 minutes. Mopane showed unexpected peaks in the NO_x concentrations, which could be attributed to the homogeneity differences in the fuelling pieces, as previously discussed. The three wood species contained meagre sulphur content, ~0.08% and consequently showed low SO₂ concentrations.

Particulate matter concentrations

Figure 4-10 shows the PM concentrations in the flue gas of one representative run of each species.

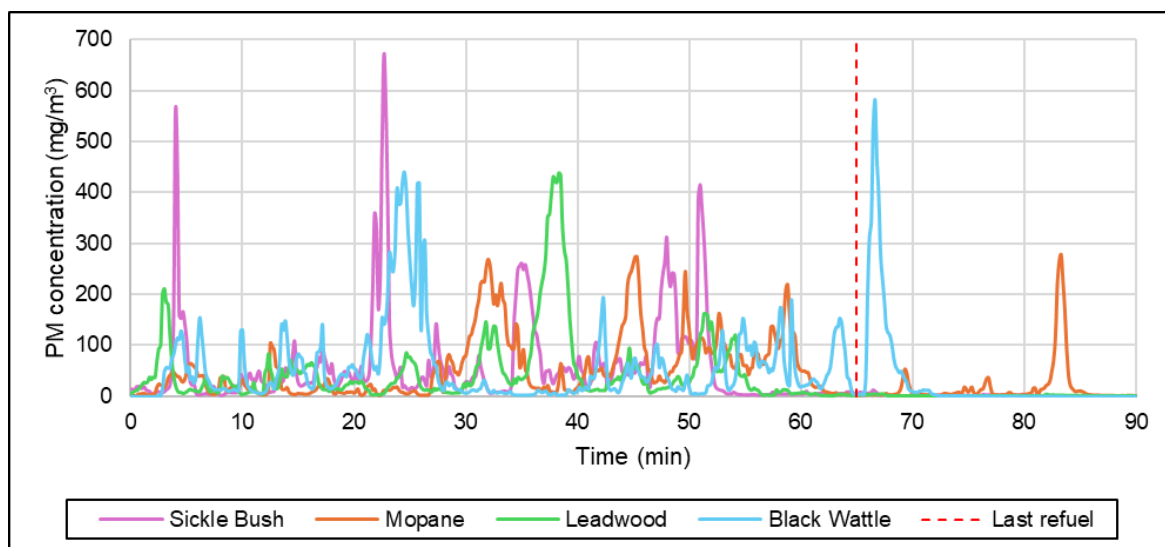


Figure 4-10: Particulate matter concentration in the flue gas of the four species throughout the 90-minute sequence.

The highest peaks are seen from the Sickle Bush and Black Wattle, the two faster-burning species. This is correlated with the use of oxygen and the incomplete combustion that takes place (Figure 4-8). Peaks are observed during the first 10 minutes after ignition, possibly due to low stove temperatures resulting in lower combustion efficiency and higher PM formation. Leadwood shows one peak just after 35 minutes, which could be due to the initiation of the water heating test at ~30 minutes. The temperature of the pots used in the testing influences the PM concentration; the placement of a cold pot increases PM, as reported by L'Orange, Volckens, *et al.* (2012). Mopane demonstrated the overall lowest PM concentration, with one peak near the end of the 90 minutes. The homogeneity of the wood samples once again influences the emission concentrations, but for PM, any disturbances in the combustion chamber could also result in a peak. An implosion of burning cuttings (around 80 minutes), or any airflow fluctuations, can cause ash to migrate from the grate, through the stove and out through the chimney, where these particles are classified and measured as particulate matter. This can also contribute to disturbances in other emissions.

4.4 Thermal performance

The water heating test and the stove's thermal efficiency are considered part of the stove's thermal performance.

4.4.1 Water heating test

Table 4-7 shows the parameters as determined by the water heating test.

Table 4-7: The amount of fuel, time to heat 1.6 L of water, maximum fuel bed temperature, SFC and the power output of each phase per species.

Water Heating Test					
Power	Fuel used (g)	Duration (min)	Power (kW)	Max. fuel bed temp (°C)	SFC (g/L)
Sickle Bush					
High	168 ± 170	8 ± 0.5	6.0 ± 6.0	862 ± 55	0.10 ± 0.1
Medium	157 ± 64	11 ± 3.7	4.4 ± 2.3	897 ± 23	0.10 ± 0.0
Low	118 ± 225	12 ± 6.3	3.0 ± 6.1	856 ± 100	0.07 ± 0.1
Mopane					
High	225 ± 76	15 ± 9.4	4.6 ± 1.9	785 ± 71	0.14 ± 0.00
Medium	158 ± 45	16 ± 3.6	2.8 ± 0.2	814 ± 125	0.10 ± 0.00
Low	137 ± 57	25 ± 14.4	1.7 ± 0.6	730 ± 166	0.09 ± 0.00
Leadwood					
High	228 ± 114	13 ± 2.4	5.0 ± 2.0	747 ± 64	0.14 ± 0.01
Medium	172 ± 25	15 ± 5.3	3.5 ± 0.9	755 ± 49	0.11 ± 0.00
Low	128 ± 80	20 ± 10.9	2.1 ± 2.6	748 ± 22	0.08 ± 0.00
Black Wattle					
High	226 ± 16	13 ± 3.5	5.0 ± 0.9	819 ± 92	0.14 ± 0.13
Medium	141 ± 42	12 ± 2.7	3.3 ± 0.3	831 ± 192	0.09 ± 0.06
Low	140 ± 165	15 ± 8.7	2.6 ± 1.9	796 ± 110	0.09 ± 0.00

The heating times and the cooking power output show the change in power, from high to low, between the three phases. Less fuel was used to heat the water as the test proceeded. The stove is heated from the start of ignition, which means that the stove is hotter by the third phase than in the first phase. This and a lower air supply could lower fuel consumption in the later phases.

The Sickle Bush, the fastest-burning species, demonstrated the highest cooking power for the three phases. This is attributed to Sickle Bush's higher burning rate and the short time required to bring the water temperature to 80 °C. The high fuel bed and flame temperatures seen from Sickle Bush also heat the stove more internally than the other species, meaning a higher stove temperature in a shorter duration and, consequently, a quicker water heating time. The shortest time recorded was in phase one of the Sickle Bush test. Mopane and Leadwood achieved lower cooking power outputs, and both species took longer to heat water to 80 °C due to their lower

fuel-burning rates, which Makonese and Bradnum (2018) reported while testing Black Wattle and different cookstoves. Mopane was observed to produce the least heat and power and take the longest time to complete the water heating test overall. Consequently, Mopane showed the lowest cooking power output in each phase. The longest heating time is attributed to the third phase using Mopane. Mopane and Leadwood also showed the highest SFC per phase.

The difference between the performance of the species can be seen in the difference in the maximum fuel bed temperature per phase. Sickle Bush and Black Wattle reached temperatures above 800 °C in the first phase already, while Leadwood and Mopane only reached temperatures up to 785 °C. Although Sickle Bush used less fuel than Mopane for the first phase, the power was higher in this phase. This could be caused by the higher fuel bed temperatures and quicker heating times observed from Sickle Bush.

Sickle Bush provided heat the quickest, as seen by the short boiling durations. A user could use this species for bathing when they require boiling water quickly, while a species like Leadwood can be used for longer cooking durations.

Makonese and Bradnum (2018) reported a heating time (1 L of water) between 5.8 and 8.5 minutes, depending on the stove configuration. The test consisted of one high-power phase. Small hopper stoves like the Flamingo™ stove demonstrated longer heating times than large hopper stoves (Makonese & Bradnum, 2018). The Flamingo™ stove exhibited higher heating times, which is expected since more water (1.6 L) was used in the test. However, when the time to heat 1 L of water was determined, the Flamingo™ stove demonstrated between 5 and 15 minutes over all three power phases. For high-power tests on an improved TLUD cookstove using woodchips and wood pellets, heating times of 15 and 15.5 minutes were reported using 2 L of water (Sonarkar & Chaurasia, 2019). This same study compared the improved cookstove to traditional stoves and found faster heating times for cold starts, and higher heating times for a hot start testing sequence (Sonarkar & Chaurasia, 2019). Black Wattle and Sickle Bush resulted in quicker heating times due to high firepower, but the use of Leadwood and Mopane is comparable to the above studies.

4.4.2 Thermal efficiency

Table 4-8 shows the results of the thermal, or cooking, efficiency tests using the four species.

Table 4-8: Thermal efficiency for each phase of the HTP in each pot for the four species.

Thermal efficiency (%)			
Power	Primary pot	Secondary pot	Effective
Sickle Bush			
High	13.2 ± 17.6	8.3 ± 8.1	21.5 ± 24.8
Medium	9.4 ± 3.6	6.1 ± 2.3	15.5 ± 5.9
Low	9.0 ± 4.5	3.6 ± 4.5	12.6 ± 6.7
Mopane			
High	7.47 ± 4.0	2.6 ± 2.9	10.0 ± 7.0
Medium	12.4 ± 7.7	4.0 ± 5.1	16.5 ± 9.8
Low	11.9 ± 5.2	7.2 ± 2.9	19.1 ± 8.0
Leadwood			
High	8.5 ± 4.8	4.7 ± 3.5	13.3 ± 7.7
Medium	11.7 ± 1.8	5.4 ± 2.8	17.1 ± 1.5
Low	16.1 ± 9.2	9.3 ± 9.5	25.4 ± 18.5
Black Wattle			
High	8.7 ± 4.3	4.5 ± 3.6	13.2 ± 7.7
Medium	12.5 ± 4.8	6.1 ± 3.6	18.5 ± 7.0
Low	16.9 ± 12	9.2 ± 9.3	26.2 ± 21.2

A higher thermal efficiency was observed in the primary pot for each phase. This is due to the placement of the cooking hob, located directly above the combustion chamber, in closer contact with the fire.

An increase in cooking efficiency is seen from the first phase to the third, along with a decrease in the power of the phases (Table 4-7). This is due to the surface heating – the surface temperature in the final phase is higher than in the first, resulting in a higher thermal efficiency. The thermal efficiency is determined by the amount of energy transferred from the fuel to the water pot, regardless of the heating time, and a higher efficiency is observed despite the longer heating times.

Overall, Sickle Bush showed the highest efficiency in the first phase but the lowest in the second and third phases. Mopane resulted in the lowest effective efficiency, which could be attributed to the lower heat availability from Mopane. Mopane was observed as the longest burning species, taking the longest time to heat the stove, along with the lowest flame temperatures, and thus, the lower efficiency in water heating. Leadwood and Black Wattle had higher efficiencies in primary and secondary pots.

Makonese and Bradnum (2018) reported 24–33% efficiencies for one pot heating 5 L of water, higher than the Flamingo™ stove. The Flamingo™ stove is a multi-pot stove; the effective thermal efficiency can be determined by adding the efficiency observed in each pot. If the efficiency of both pots is considered, the values are in a closer range. The thermal efficiency of a TLUD stove, using wood pellets and coconut shells, was 25% and 27%, respectively. (Sonarkar & Chaurasia, 2019). Obeng *et al.* (2017) used a wood cookstove and similar wood cuttings for the Flamingo™ stove, which showed an efficiency of 12.2% comparable to the Flamingo™ stove.

4.5 Emission performance

4.5.1 Emission factors

The emission factors for the pollutants are reported in g/MJ. Again, the oven flap is horizontal for the values reported in this section.

NO_x and SO₂ emission factors

Table 4-9 shows the mass of NO_x emitted, as well as the emission factors, for each species.

Table 4-9: NO_x emission rates (g/h) and emission factors for each species.

		Sickle Bush	Mopane	Leadwood	Black Wattle
NO _x emission rate	g/hr	1.8 ± 0.6	1.2 ± 0.0	0.6 ± 0.1	1.2 ± 0.0
NO _x emission factor	g/MJ	0.13 ± 0.0	0.08 ± 0.00	0.08 ± 0.01	0.08 ± 0.01

As discussed in Section 4.3.2, the temperatures of the cookstove are too low for thermal NO_x to form; hence, the NO_x emissions are attributable to the nitrogen content in the fuelwood (fuel-N). Sickle Bush showed the highest emission factors for NO_x, while Leadwood and Mopane showed the lowest emission factors. From Figure 4-9, Sickle Bush shows prominent peaks in the NO_x concentration throughout the 90-minute period, which are not seen from the other species. This could be attributed to the higher NO_x emission factors shown by the species because of the high burn rate and power output.

Concerning the nitrogen content of each species, Sickle Bush had the second highest fuel-N (0.49%) after Black Wattle (1.7%), while Leadwood and Mopane had the two lowest fuel-N contents at 0.22 and 0.35%, respectively. This trend is observed in the emission factors since Sickle Bush and Black Wattle demonstrated the highest emission factors for NO_x, while Leadwood and Mopane showed the lowest emission factors. Leadwood, with the lowest nitrogen content, emitted NO_x at the lowest rate, while Black Wattle, with the highest nitrogen content, only emitted the second-highest mass rate of NO_x.

The species showed comparable NO_x emission factors when compared to previous studies (Table 4-13). Other studies reported values between 0.005–0.186 g/MJ for cookstoves using biomass and a value of 0.63 g/MJ for coal (Bhattacharya, Albina & Abdul Salam, 2002; Champion *et al.*, 2021; Deng *et al.*, 2022). The difference in emission factors between studies could be attributed to the differing fuel-N content. The four species and the Flamingo™ stove show a significant decrease in the emission factor compared to coal.

Table 4-10 shows the mass of SO₂ emitted, as well as the emission factors, for each species.

Table 4-10: SO₂ emission rates and emission factors for each species.

		Sickle Bush	Mopane	Leadwood	Black Wattle
SO ₂ emission rate	g/hr	0.06 ± 0.06	1.8 ± 1.2	0.6 ± 0.0	1.8 ± 1.2
SO ₂ emission factor	g/MJ	0.06 ± 0.01	0.13 ± 0.3	0.04 ± 0.00	0.04 ± 0.00

SO₂ emissions are also closely related to the fuel-S content. The SO₂ emission factor for each species is in a low range, related to the low fuel-S in each species (0.08%). The four species showed the same sulphur content but demonstrated different results for the emission rate and the consequent emission factors – factors such as temperature and unreacted sulphur play a role in this. Leadwood and Black Wattle showed the lowest emission factor for SO₂, while Mopane showed the highest. Black Wattle showed the highest emission rate of SO₂ but also the lowest emission factor. This is the opposite trend, as seen from the mass of SO₂ emitted from Mopane, where the high emission rate resulted in the highest emission factor. Due to the similar CV values, this change can only be attributed to the mass of fuel used during the test sequences of each species. Black Wattle's high conversion resulted in more fuel being burnt during the 90-minute run.

Few studies determine the emission factors for SO₂, but two studies (Table 4-13) reported low SO₂ emission factors between 0–0.093 g/MJ, including an emission factor for coal. Only Mopane showed emission factors outside this range, while the other four species showed comparable results. The emission factors are negligible due to the low sulphur content of biomass.

CO and CO₂ emission factors

Table 4-11 shows the CO and CO₂ emission rates and emission factors for each species, along with the emission factors.

Table 4-11: CO and CO₂ emission rates and emission factors.

		Sickle Bush	Mopane	Leadwood	Black Wattle
CO ₂ emission rate	g/hr	1 450 ± 235	1 129 ± 85	1 016 ± 77	1 183 ± 146
CO ₂ emission factor	g/MJ	91 ± 6.3	95 ± 1.0	103 ± 8.6	94 ± 3.1
CO emission rate	g/hr	64 ± 5	37 ± 4	31 ± 1	44 ± 7
CO emission factor	g/MJ	4.1 ± 1.1	3.1 ± 0.1	3.2 ± 1.0	3.1 ± 1.4
CO/CO ₂ ratio		0.04 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01

Sickle Bush exhibited the highest CO emission factor, while the remaining three species showed similar, lower values. The high CO emission factor for Sickle Bush may be due to the rapid combustion and the ensuing oxygen depletion, as discussed in Section 4.3.2. Sickle Bush showed the lowest CO₂ emission factor, producing the highest CO/CO₂ ratio. The correlation between Sickle Bush's CO and CO₂ emission factors indicates the degree of complete and incomplete combustion due to Sickle Bush's high burning rate. Leadwood, in comparison, exhibited the highest degree of complete combustion, as seen by its low CO/CO₂ ratio.

The formation of CO and CO₂ is dependent on various factors, such as stove temperatures, fuel composition, oxygen levels, residence time and mixing of combustible gases (Wei *et al.*, 2012). Although Leadwood and Mopane showed the lowest fuel bed temperatures, which should lead to lower CO₂ formation, the lower velocity of Leadwood could result in a sufficient residence time for complete combustion. The emission factors for the three species are similar, with Leadwood as an outlier. Leadwood should produce lower emission factors based on its lower carbon content, but in contrast, the highest emission factor for CO₂ is demonstrated from Leadwood. The larger emission factor could be attributed to the low CV value determined for Leadwood – less CO₂ should be emitted for the energy released from the fuel for the emission factor to be more acceptable.

The mass emission rate (g/hr) of both CO and CO₂ shows the same trend over the four species. The two faster-burning species, Sickle Bush and Black Wattle, demonstrated the highest CO and CO₂ emission rates. In contrast, Mopane and Leadwood, with lower burn rates and lower conversion, showed a lower emission rate of each pollutant.

Referring to Table 4-13, the CO emission factors seen from the Flamingo™ stove are in the acceptable range, as seen in other studies. Values between 0.005–4.5 g/MJ have been reported (Bentson *et al.*, 2022; Bhattacharya, Albina & Abdul Salam, 2002; Champion *et al.*, 2021; Deng *et al.*, 2022; Huangfu *et al.*, 2014; Wei *et al.*, 2012). The CO emission factors determined from the four species fall within this range, albeit to the higher end. The CO emission factor is a parameter used in the ISO tier performance standard discussed in Section 4.7.

CO₂ is slightly higher than in some studies, but one study on raw wood found similar emission factors (Wei *et al.*, 2012). Values between 81–106 g/MJ have been reported, comparable to the Flamingo™ stove and the local wood species.

PM emission factors

Table 4-12 shows the mass of PM emitted and the emission factors for each species.

Table 4-12: PM emitted and the emission factors for each species.

		Sickle Bush	Mopane	Leadwood	Black Wattle
PM emission rate	g/hr	1.3 ± 0.6	1.3 ± 0.2	0.7 ± 0.1	2.7 ± 2.4
PM emission factor	g/MJ	0.11 ± 0.01	0.11 ± 0.00	0.10 ± 0.00	0.06 ± 0.00

For particulate matter, Sickle Bush and Mopane exhibited the highest emission factor, likely due to the degree of incomplete combustion, as indicated by their higher CO/CO₂ ratio (L'Orange, Volckens, *et al.*, 2012). On the contrary, Black Wattle and Leadwood showed the lowest emission factors, even though Black Wattle showed the highest emission rate of PM. This difference could be attributed to Black Wattle's higher calorific value and its higher degree of conversion.

The three slower-burning species, Mopane, Leadwood and Sickle Bush, produced lower PM emission rates, while Black Wattle demonstrated higher emission rates. This is likely attributed to the depletion of oxygen and consequent higher levels of incomplete combustion, as discussed in Section 4.3.2 (Deng *et al.*, 2020).

Another key factor known to influence the emission of PM is the moisture content. A higher moisture content tends to reduce combustion efficiency and results in higher PM emissions. Black Wattle should produce higher PM emissions due to the high moisture content, as seen by the mass of PM emitted (van Zyl *et al.*, 2019). In contrast, although Sickle Bush showed the lowest moisture content, it emitted higher PM values than Mopane and Leadwood, which have a lower moisture content.

PM emission factors reported in the literature (Table 4-13) vary significantly, 0.01–2.4 g/MJ. The reported emission factors for the Flamingo™ stove are in the lower spectrum of this range but still comparable. In comparison, the Flamingo™ stove performs well against other stoves concerning PM. PM is also a tier parameter, which is further discussed in Section 4.7.

Comparison

As discussed above, the reported emission factors are comparable to findings in the literature for other improved cookstove models. Table 4-13 shows studies that have reported emission factors for cookstoves using biomass and one study using coal. NO_x and SO₂ emission factors fall within the ranges reported. CO and CO₂ emission factors are in the same range but fall into the higher spectrum of the range. Lastly, the PM emission factor is on the lower side of the reported ranges. For further comparison, refer to Section 4.7, for the tier performance discussion.

Table 4-13: Emission factors reported in previous studies.

Study	Stove type	Fuel	Emission factors (g/MJ)				
			NO _x	SO ₂	CO	CO ₂	PM
This study	Flamingo™ stove	Four species	0.08–0.13	0.04–0.13	3.0–4.3	89–103	0.06–0.13
Makonese and Bradnum (2018)	Six stove types	Black Wattle	-	-	0.01–2.66	-	0.7–2.4
Bhattacharya, Albina and Abdul Salam (2002)	24 stove types	Pine	0.005–0.01	-	0.97–2.66	81–82	-
Deng <i>et al.</i> (2022)	Pellet stove	Wood pellets	0.19	0	0.11	-	0.01
-	Heating stove	Bituminous coal	0.63	0.09	1.25	-	0.15
Bentson <i>et al.</i> (2022)	Six stove types	Unspecified wood	-	-	2.4–11.2	-	0.39–1.34
Champion <i>et al.</i> (2020)	Three stove types	Hardwood pellets	0.15–0.19	-	1.63–2.98	-	0.04–0.07
Huangfu <i>et al.</i> (2014)	Natural draft stove	Pellets (different moisture contents)	-	-	2.5–4.5	-	0.2–0.58
Wei <i>et al.</i> (2012)	Brick Wok Stove	Five wood species	-	-	1.9–3.3	87–106	-

4.6 Influence of the use of the oven

The novel feature of the stove is the use of an oven. The influence of the two different oven configurations on the thermal and emission performance was investigated.

4.6.1 Oven temperatures

Figure 4-11 and Figure 4-12 show the temperature profiles of the four thermocouples measuring inside the oven (IO-01T, IO-02L, IO-03B, IO-04R in Figure 3-8). Both the oven in use and the oven not in use are shown. Only one run using Black Wattle as fuel is shown for the first set of figures.

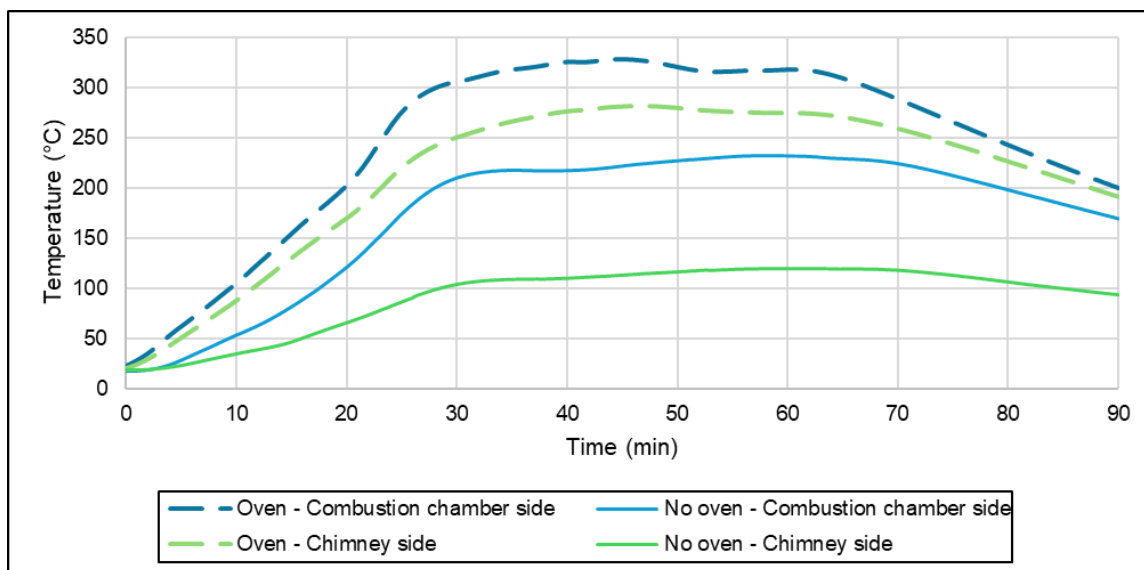


Figure 4-11: Change in oven temperature on both sides of the oven.

The second-highest oven temperature is measured on the combustion chamber side of the oven because of its placement directly next to the combustion chamber. Although hot air does not come into direct contact with the oven, the heat is conducted throughout the walls of the stove.

The combustion chamber side of the oven reaches higher temperatures when the oven is in use since hot air is now allowed to flow in direct contact with the left side of the oven. The right-hand side of the oven is the farthest away from the fire, and temperatures do not exceed 200 °C when the flap is in a horizontal position. A noticeable increase is observed in the oven's temperature on the right side. Hot air is in direct contact with the oven, resulting in a higher overall temperature within the oven.

Figure 4-12 shows the change in the oven temperatures at the top and bottom.

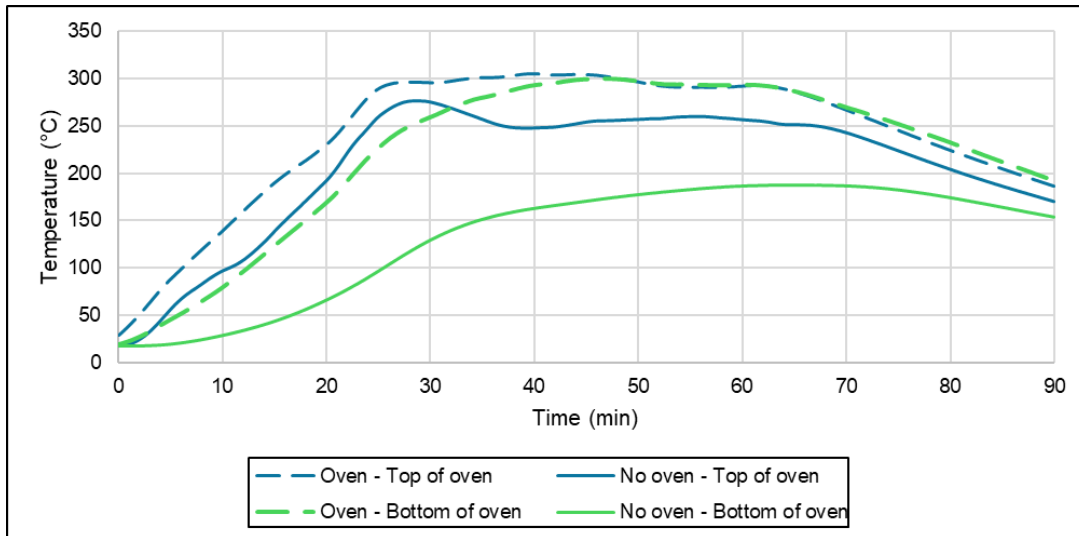


Figure 4-12: Time variation of the top and bottom oven temperatures.

The highest temperature within the oven is measured at the top of the oven. This is due to the hot air flowing being directed only above the oven – the top of the oven is in the closest contact with the heat. The maximum temperature observed without the use of the oven is 275 °C.

When the oven is in use (flap vertical), the temperature at the top of the oven does not differ as much from the flap-down configuration. Hot air is still allowed to pass through a gap in the oven control flap (Figure 3-4). Consequently, similar temperatures are observed even when the oven is used. When the oven is used, the temperature reaches just above 300 °C.

With the flap in the horizontal position, the temperature at the bottom of the oven exceeds 200 °C. The heat in this area is due to the overall temperature rather than the airflow direction. The bottom temperature of the oven increases significantly between the two oven configurations. A maximum temperature of 300 °C is reached. This shows the increase in heat at the bottom of the oven since the hot air is again allowed to flow around the oven.

Baking is usually done at a temperature between 180–210 °C. The oven temperatures would not be suitable for baking. With the flap in the horizontal position, the top of the oven still reaches temperatures up to 250 °C, and the bottom reaches almost 200 °C, which is still higher than the desirable temperatures for baking. The chimney side of the stove only reaches around 125 °C, which is lower than the necessary temperature for baking. With the flap in the vertical position, the oven reaches temperatures of 300 °C, which is too high for baking purposes. At any configuration, the oven is not suitable for baking, resulting in burnt food when trying to use the oven. This could be fixed with better insulation of the oven or moving the combustion chamber to a different area, away from the oven.

Figure 4-13 shows the differing oven temperatures for each wood species.

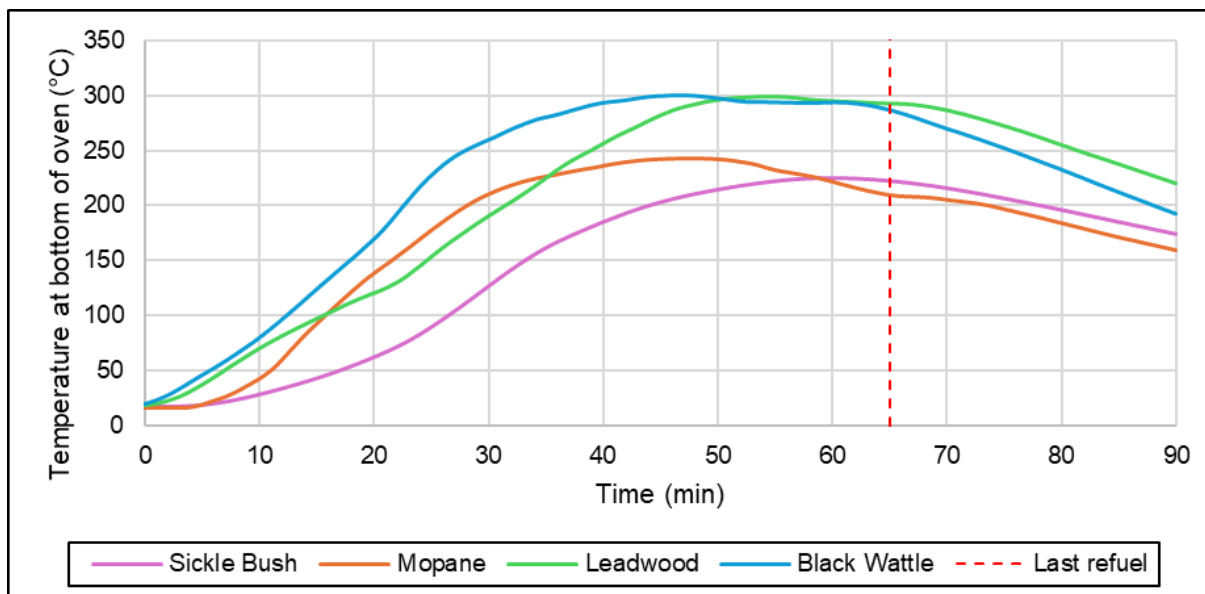


Figure 4-13: Temperature at the bottom of the oven when the oven is in use.

Sickle Bush and Mopane demonstrated oven temperatures lower than Black Wattle and Leadwood. This emphasises that the performance of the stove is reliant on the wood species used and shows that the choice of fuel depends on the user's needs.

The temperature difference between the two sides of the stove could also have implications when baking. The left-hand side of the oven, with a higher temperature, could cause the bread to bake faster and even burn on one side. It is also necessary for the user to turn the food in the oven, the same as when working in a microwave. This, unfortunately, increases the user's risk of burn injuries, which is part of the issue surrounding the use of open fires.

4.6.2 Fuel consumption and power output

For this section, each of the four species is used to investigate the influence of the use of the oven on the stove's thermal and emission performance. For the graphs, one experimental run is shown, and for the tables, the average values of three runs per species are used. Figure 4-14 shows the fuel consumption for each oven configuration for each species separately.

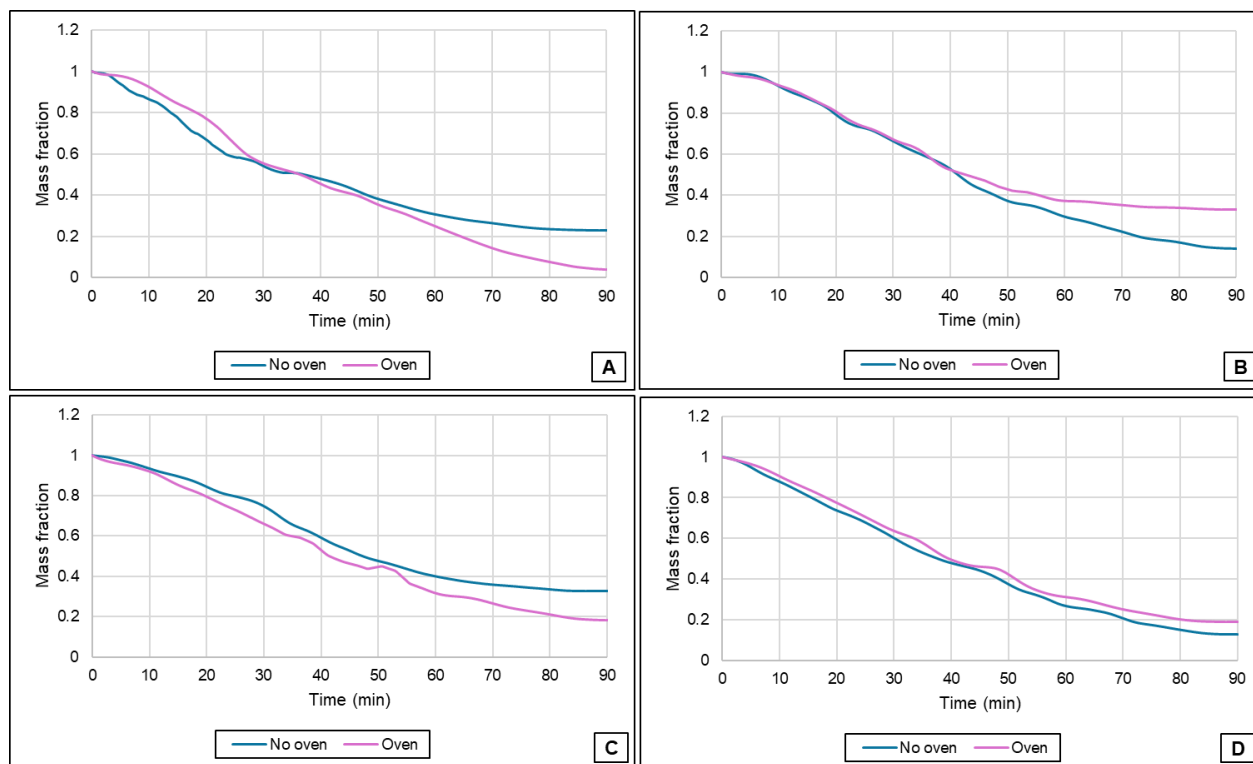


Figure 4-14: Fuel consumption for different oven configurations of A) Sickle Bush, B) Mopane, C) Leadwood, and D) Black Wattle.

The use of the oven has had different influences on different species. For Mopane and Black Wattle, a decrease in the thermal conversion after 90 minutes (relative burn rate) is observed, while an increase in the thermal conversion is seen for Sickle Bush and Leadwood. The burn rate of Sickle Bush, Mopane and Black Wattle decreased, while Leadwood showed a slight increase. The flow rate could influence the burn rate and resulting draught within the stove (Table 4-20). The use of the oven does affect the burn rate of the stove.

The power output and burn rates of each species are shown in Table 4-14. Sickle Bush and Mopane demonstrated an increase in the power output, but in contrast, Leadwood and Black Wattle showed a slight decrease. Taking the uncertainties into account, it is seen that the changes in power output are almost insignificant. It is concluded that the use of the oven does not influence the power output of the stove.

Table 4-14: Comparison of power between oven configurations.

		Sickle Bush	Mopane	Leadwood	Black Wattle
No Oven					
Burn rate	g/min	14.2 ± 3.0	10.2 ± 2.5	10.2 ± 2.80	11.1 ± 4.30
Power output	kW	4.1 ± 1.80	3.1 ± 0.70	2.8 ± 0.80	3.1 ± 1.10
Oven					
Burn rate	g/min	12.7 ± 0.6	8.3 ± 0.4	10.8 ± 1.6	11.0 ± 1.1
Power output	kW	3.9 ± 0.2	2.5 ± 0.1	2.9 ± 0.4	3.3 ± 0.3

Table 4-15 shows the p-values between the two configurations.

Table 4-15: P-values for burn rate and firepower for the two configurations.

		Sickle Bush	Mopane	Leadwood	Black Wattle
Ratio of difference (p-value)					
Burn rate	g/min	1.18	1.06	1.23	1.18
Power output	kW	1.17	1.07	1.21	1.41

Insignificant differences are observed between the two configurations for the different configurations, as seen by the p-values smaller than 2.

4.6.3 Water heating test and thermal efficiency

The fuel used, and the duration and power output for each species and each configuration are shown in Table 4-16.

Table 4-16: Comparison of water heating parameters between oven configurations.

Water Heating Tests						
	No oven			Oven		
Power setting	Fuel used (g)	Duration (min)	Power (kW)	Fuel used (g)	Duration (min)	Power (kW)
Sickle Bush						
High	168 ± 170	8 ± 0.5	6.0 ± 6.0	154 ± 28	10 ± 2	4.6 ± 0.3
Medium	157 ± 64	11 ± 3.7	4.4 ± 2.3	106 ± 10	10 ± 4	2.1 ± 0.6
Low	118 ± 225	12 ± 6.3	3.0 ± 6.1	147 ± 19	19 ± 10	2.3 ± 0.6
Mopane						
High	225 ± 76	15 ± 9.4	4.6 ± 1.9	192 ± 9	12 ± 2	5.2 ± 0.9
Medium	158 ± 45	16 ± 3.6	2.8 ± 0.2	139 ± 5	18 ± 3	2.6 ± 0.5
Low	137 ± 57	25 ± 14.4	1.7 ± 0.6	88 ± 9	23 ± 6	1.3 ± 0.2
Leadwood						
High	228 ± 114	13 ± 2.4	5.0 ± 2.0	162 ± 15	8 ± 1	6.0 ± 1.2
Medium	172 ± 25	15 ± 5.3	3.5 ± 0.9	129 ± 16	9 ± 1	4.1 ± 0.7
Low	128 ± 80	20 ± 10.9	2.1 ± 2.6	99 ± 10	10 ± 2	3.1 ± 1.4
Black Wattle						
High	226 ± 16	13 ± 3.5	5.0 ± 0.9	148 ± 19	9 ± 3	4.9 ± 0.9
Medium	141 ± 42	12 ± 2.7	3.3 ± 0.3	130 ± 19	11 ± 2	3.6 ± 0.3
Low	140 ± 165	15 ± 8.7	2.6 ± 1.9	133 ± 18	14 ± 3	3.0 ± 0.7

Less fuel was used per phase when the oven was in use. Shorter durations are also observed for each pot to reach 80 °C. Higher power outputs are also achieved when the oven is in use, except for Sickle Bush, which showed decreased power output per phase. Once again, when the included uncertainties are considered, it can be concluded that the oven does not affect the amount of fuel used but does influence the heating duration and power output. Table 4-16 shows the p-values determined for each parameter between the use of the oven and use without the oven.

Table 4-17: P-values for the differences in the Water Heating Test.

Ratio of difference (p-value)			
Power setting	Fuel used (g)	Duration (min)	Power (kW)
Sickle Bush			
High	0.25	-1.37	0.33
Medium	2.43	0.26	1.37
Low	-0.41	-0.84	0.16
Mopane			
High	0.61	0.44	-0.40
Medium	0.59	-0.60	0.53
Low	1.20	0.18	0.89
Leadwood			
High	0.81	2.72	-0.61
Medium	2.05	1.57	-0.74
Low	0.51	1.28	-0.48
Black Wattle			
High	5.47	1.23	0.11
Medium	0.25	0.42	-1.00
Low	1.20	0.15	-0.28

Significant differences ($p > 2$ and closer to 2) are seen in the power and fuel used when using Sickle Bush in the medium power phase. The low-power phase using Mopane showed a significant difference in fuel use. The most significant difference is seen in the fuel used during the high-power phase of Black Wattle. Less fuel was used during the sequences where the oven was used (148 g) than when the oven was not in use (226 g).

Table 4-18 compares the effective thermal efficiency obtained for both configurations using each of the four species.

Table 4-18: Comparison of thermal efficiency for the oven configurations.

Effective thermal efficiency (%)		
Power setting	No oven	Oven
Sickle Bush		
High	21.5 ± 24.8	16.5 ± 3.4
Medium	15.5 ± 5.9	23.0 ± 4.7
Low	12.6 ± 6.7	17.3 ± 5.5
Mopane		
High	10.0 ± 7.0	11.7 ± 1.5
Medium	16.5 ± 9.8	15.8 ± 1.8
Low	19.1 ± 8.0	26.7 ± 4.5
Leadwood		
High	13.3 ± 7.7	16.7 ± 1.7
Medium	17.1 ± 1.5	21.1 ± 2.5
Low	25.4 ± 18.5	29.9 ± 8.1
Black Wattle		
High	13.2 ± 7.7	17.8 ± 1.6
Medium	18.5 ± 7.0	19.0 ± 3.1
Low	26.2 ± 21.2	19.5 ± 2.7

The secondary plate shows a decreased thermal efficiency when the oven is used. This is due to a lower secondary hob temperature since the hot air is no longer in direct contact with the hob. The efficiency in the primary pot increased, which increased the total thermal efficiency, as seen in Table 4-18. The increase in the primary pot could be attributed to a longer residence time of hot air in the combustion chamber directly beneath the primary cooking hob. The hot air follows a higher resistance path when flowing around the oven, as seen by the lower draught, and remains in the chamber for longer. The use of the oven thus influences the thermal efficiency of the stove.

Table 4-19 shows the p-values for thermal efficiency between the two configurations.

Table 4-19: P-values for thermal efficiency differences.

Effective thermal efficiency (%)	
Ratio of difference	
Sickle Bush	
High	-0.28
Medium	1.41
Low	0.77
Mopane	
High	0.34
Medium	-0.10
Low	1.17
Leadwood	
High	0.61
Medium	1.94
Low	0.32
Black Wattle	
High	0.83
Medium	0.09
Low	-0.44

The most significant difference is using Leadwood during the medium power phase. An increase from 17.1 to 21.1% is observed when using the oven in this configuration.

4.6.4 Emission factors

Table 4-20 shows the change in the average volumetric flow rate of each configuration.

Table 4-20: Average volumetric flow rate for each species and configuration.

		Sickle Bush	Mopane	Leadwood	Black Wattle
No oven	m ³ /min	0.5 ± 0.1	0.7 ± 0.3	0.4 ± 0.1	0.9 ± 0.7
Oven	m ³ /min	0.8 ± 0.2	0.5 ± 0.20	0.7 ± 0.3	0.4 ± 0.1

The flow rate decreases for Mopane and Black Wattle but, in contrast, increases for Sickle Bush and Leadwood. The decrease in flow rate is attributed to a lower draught caused by the resistance brought on by the plate in the vertical position. The uncertainties do, however, eliminate any significant changes. The oven's use does influence the stove's flow rate slightly.

Table 4-21 shows the difference in emission factors for the two stove configurations.

Table 4-21: Emission factor comparison for oven configurations.

Emission factors (g/MJ)					
	NO _x	SO ₂	CO	CO ₂	PM
Sickle Bush					
No oven	0.06 ± 0.01	91 ± 6.3	4.1 ± 1.1	0.11 ± 0.01	0.06 ± 0.01
Oven	0.11 ± 0.01	0.12 ± 0.02	5 ± 0.8	87 ± 4	0.09 ± 0.02
Mopane					
No oven	0.13 ± 0.3	95 ± 1.0	3.1 ± 0.1	0.11 ± 0.00	0.13 ± 0.3
Oven	0.11 ± 0.02	0.06 ± 0.01	4.3 ± 0.6	96 ± 2.0	0.26 ± 0.16
Leadwood					
No oven	0.08 ± 0.01	0.04 ± 0.00	103 ± 8.6	3.2 ± 1.0	0.10 ± 0.00
Oven	0.10 ± 0.01	0.06 ± 0.02	3.3 ± 0.3	104 ± 4.0	0.10 ± 0.01
Black Wattle					
No oven	0.08 ± 0.01	0.04 ± 0.00	94 ± 3.1	3.1 ± 1.4	0.06 ± 0.00
Oven	0.10 ± 0.01	0.10 ± 0.04	4.3 ± 0.3	93 ± 1.0	0.09 ± 0.02

For the NO_x emission factors, the values are the same or similar, considering the uncertainties. As previously discussed, the temperatures are too low for thermal NO_x to form. The production of NO_x depends on the fuel-N content, implying that no change should occur because of the oven configuration. The same is considered for SO₂ – the observed changes in the emission factor are small since SO₂ depends on the fuel-S content. The use of the oven does not have a significant influence on the NO_x and SO₂ emission factors.

An increase in the CO emission factor is observed for the four species. This change could be attributed to a lower draught, a lower O₂ concentration, and an increase in the degree of incomplete combustion. The CO₂ emission factors should coincide with the trend for the CO emission factors, which is true, except for Mopane. Mopane demonstrated a dramatic increase in CO₂ emission factors. Lastly, an increase in the PM emission factors is observed for three of the species, except for Sickle Bush. This increase can be related to the higher degree of incomplete combustion since incomplete combustion is related to the production of PM (Kshirsagar & Kalamkar, 2016). Table 4-22 shows the p-values for the difference between the two configurations.

Table 4-22: P-values for the different emission factors.

Emission factors (g/MJ)					
Ratio of difference					
	NO _x	SO ₂	CO	CO ₂	PM
Sickle Bush					
p-value	-2.83	3.79	0.25	-0.76	-1.26
Mopane					
p-value	2.12	-0.33	0.42	0.63	1.33
Leadwood					
p-value	2.00	1.41	0.14	0.15	0.00
Black Wattle					
p-value	2.00	2.12	0.24	-0.43	2.12

The most significant change is observed in the SO₂ emission factor for Sickle Bush and the NO_x emission factor for Sickle Bush and Mopane. Overall, the use of the oven has a greater impact on the NO_x and SO₂ emission factors, but a smaller impact on CO, CO₂ and PM emission factors.

Considering the uncertainties, it can be concluded that the use of the oven does not affect the emission factors of the Flamingo™ stove. Although significant changes in specific parameters are seen, the use of the oven does not influence the operation of the Flamingo™ stove significantly.

4.7 Tier performance of different species

To ensure compliance with international requirements, the stove performance is related to the ISO voluntary performance tiers (Figure 2-10 in Section 2.7.2). Table 4-23 shows the emission and thermal efficiency tiers as demonstrated by the four species.

Table 4-23: CO and PM emission and thermal efficiency tier classification of each species without the oven in use.

Species		ISO Criteria					
	CO EF (g/MJ)	CO < 3.0 g/MJ	CO < 4.4 g/MJ	CO < 7.2 g/MJ	CO < 11.5 g/MJ	CO < 18.3 g/MJ	CO > 18.3 g/MJ
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	4.1 ± 0.4		X				
Mopane	3.1 ± 0.4		X				
Leadwood	3.2 ± 0.5		X				
Black Wattle	3.1 ± 0.6		X				
	PM EF (g/MJ)	PM < 5 mg/MJ	PM < 62 Mg/MJ	PM < 280 Mg/MJ	PM < 480 Mg/MJ	PM < 1030 Mg/MJ	PM > 1030 mg/MJ
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	0.11 ± 0.00			X			
Mopane	0.11 ± 0.00			X			
Leadwood	0.10 ± 0.00			X			
Black Wattle	0.06 ± 0.01		X				
	Thermal eff. (%)	Thermal eff. ≥ 50 %	Thermal eff. ≥ 40 %	Thermal eff. ≥ 30%	Thermal eff. ≥ 20%	Thermal eff. ≥ 10%	Thermal eff. < 10%
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	21.5 ± 9.2				X		
Mopane	19.1 ± 3.0					X	
Leadwood	25.4 ± 6.9				X		
Black Wattle	26.2 ± 7.9				X		

The Flamingo™ stove showed CO emission performance equivalent to a Tier 4 for the four wood/stove combinations. This is the second highest tier, for which the CO emission factor should be below 4 g/MJ. The only Tier 4 stove-species combination concerning PM emissions is Black Wattle. The other three stove-species combinations, with higher PM emissions, demonstrated Tier 3 performance.

The stove did not perform well in the thermal efficiency section, delivering Tier 1 and Tier 2 performances. From Table 5-18, Black Wattle exhibits the best performance among the four species, having the highest tier scores for the three sections.

The use of the oven slightly influences the tier performance of the stove, as seen in Table 4-20 (referring to Figure 2-9 in Section 2.7.1).

Table 4-24: CO and PM emission and thermal efficiency tier classification of each species with the oven in use.

Species		ISO Criteria					
	CO EF (g/MJ)	CO < 3.0 g/MJ	CO < 4.4 g/MJ	CO < 7.2 g/MJ	CO < 11.5 g/MJ	CO < 18.3 g/MJ	CO > 18.3 g/MJ
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	5 ± 0.8			X			
Mopane	4.3 ± 0.6		X				
Leadwood	3.3 ± 0.3		X				
Black Wattle	4.3 ± 0.3		X				
	PM EF (g/MJ)	PM < 5 mg/MJ	PM < 62 Mg/MJ	PM < 280 Mg/MJ	PM < 480 Mg/MJ	PM < 1030 Mg/MJ	PM > 1030 mg/MJ
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	0.09 ± 0.02			X			
Mopane	0.26 ± 0.16			X			
Leadwood	0.10 ± 0.01			X			
Black Wattle	0.09 ± 0.02			X			
	Thermal eff. (%)	Thermal eff. ≥ 50 %	Thermal eff. ≥ 40 %	Thermal eff. ≥ 30%	Thermal eff. ≥ 20%	Thermal eff. ≥ 10%	Thermal eff. < 10%
	This study	Tier 5	Tier 4	Tier 3	Tier 2	Tier 1	Tier 0
Sickle Bush	23.0 ± 4.7				X		
Mopane	26.7 ± 4.5				X		
Leadwood	29.9 ± 8.1				X		
Black Wattle	19.5 ± 2.7					X	

The thermal performance is seen to improve for two species, moving from Tier 1 to Tier 2. Black Wattle decreased to a Tier 1. Sickle Bush decreased CO tier performance from Tier 4 to Tier 3, while Black Wattle moved to Tier 3 for PM emission performance.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study identified Sickle Bush, Mopane, Leadwood, and Black Wattle as popular fuel species used in the Limpopo province of South Africa, based on published community surveys and personal communication with a fellow researcher specialising in this study area. Black Wattle is also a popular choice in other parts of South Africa since it is widely available.

The Chemical Engineering Department provided the stove technology as part of their larger stove/fuel research agenda. A Flamingo™ stove prototype has been made available for research purposes. It had not been tested previously and had novel features not often seen in other cookstove models. The key variable assessed in this study was the four different fuel species, all limited to a uniform size. Fixed operating procedures and the uniformity of the wood enabled the comparison between the different species' emission and thermal performance parameters.

In testing various wood species for use in the Flamingo™ stove, the Sickle Bush emerged as the fastest-burning species, showing the highest maximum fuel bed temperatures. Sickle Bush also showed the highest power output, at 4.1 ± 0.8 kW, in contrast to the low power shown by Leadwood at 2.8 ± 0.3 kW. Black Wattle provided the quickest heating times during the water heating test. Mopane demonstrated the lowest effective thermal efficiency, 10.0–19.1%, over the three power phases, taking the longest to heat water and losing its heat quickly. On the contrary, Leadwood exhibited consistently elevated temperatures, with high thermal efficiencies, showing a thermal efficiency of $25.4 \pm 8.2\%$ in the low power phase of the sequence. Leadwood also showed the greatest ability to retain heat after refuelling was stopped. Black Wattle showed the highest effective thermal efficiency.

Continuous refuelling could deter users from using the stove since higher fuel consumption and running costs could be assumed from continuous refuelling. Although continuous refuelling is necessary, the Flamingo™ stove uses less fuel (~1.2 kg) than traditional stoves to run for 90 minutes.

The four local wood species showed emission factors similar to those reported in previous studies. The NO_x and SO₂ emission factors are similar or lower than previously reported. The Flamingo™ stove showed NO_x emission factors between 0.08–0.13 g/MJ and SO₂ emission factors between 0.04–0.13 g/MJ. Leadwood showed the highest CO₂ emission factor, 103 ± 4 g/MJ, which is high compared to other stove models. The remaining three species demonstrated CO₂ emission factors between 91–96 g/MJ. CO emission factors, between 3.0–4.3 g/MJ, are comparable to previous studies since they were in a similar range. The faster-burning woods, Sickle Bush and Black Wattle led to higher degrees of incomplete combustion, as seen by their increased CO/CO₂

ratios. Lastly, a low PM emission factor range was observed, 0.06–0.11 g/MJ. Overall, emissions of the hardwood species were similar to other clean cookstove models, but slight changes in the operation and design could further improve the emission performance.

The species showed Tier 4 emission performance, specifically regarding CO emissions. Only Black Wattle showed Tier 4 performance for PM emissions, while the other species showed Tier 3 performance. Low-tier performance was observed for thermal efficiency using the four species (Tier 1 and 2). Although the ISO tiers for the fuel/stove combinations were determined, the design intent is to meet the user's need. Although the thermal efficiency performance ranks low on the tiers, the boiling times suit a user who wants to cook as needed. The additional controls provided by the Flamingo™ stove could be used to the cook's advantage.

The use of the oven resulted in minor changes in the performance parameters, with the most significant changes observed in the thermal performance of the stove. No significant changes were observed in the PM or CO emission factors between the two oven configurations; the minor changes observed in the emission factors could be due to experimental uncertainties. It is concluded that the oven does not significantly influence the power output or emissions of the stove, as seen by the low p-values ($p < 2$). The only influence observed when the oven is used is the thermal efficiency of the stove. An increase is observed in the three species' effective thermal efficiency. The medium power phase of Sickle Bush increased by 6%, while an increase of 4% is seen for the low power phase of Leadwood. Only Black Wattle demonstrated a slight decrease in efficiency when the oven was used. Although a few parameters showed changes when using the oven or not, no overall trends could be identified, and changes are considered insignificant.

The temperatures within the oven reached close to 300 °C independent of the flap position or fuel species. These are well above the range for everyday baking and roasting (180 °C to 220 °C). Deflecting the airflow around the oven by setting the flap in the vertical position allows the second hob to operate at a significantly lower temperature than the first, allowing simultaneous high-power and low-power simmering operation, an innovative feature for a small wood-fuelled stove. The use of the oven's regulating flap could be used as a method of controlling the temperature of the second cooking hob. Both cooking hobs can reach higher temperatures when the oven flap is horizontal. If the user requires lower hob temperatures, they could regulate it by changing the position of the flap.

In conjunction with local wood species, the Flamingo™ stove highlighted that different wood species significantly impact stove performance. Lower emissions and using twigs are beneficial factors for mitigating health risks and taking the pressure off forest resources. Using twigs has economic benefits since users would not need to purchase fuelwood, and it also encourages the use of tree litter rather than cutting down large trees or branches. The various user controls, the

many functions, and the use of twigs can be motivating factors for using the Flamingo™ stove. Due to the unreliable electricity supply in Southern African countries, appliances such as the Flamingo™ stove have a market.

The Flamingo™ stove has the potential for enhancements to elevate its emissions and thermal performance and improve its ranking within the ISO tiers. Despite these opportunities, it effectively meets user requirements, aligning with its intended design objective.

5.2 Recommendations

For future studies, the following recommendations are proposed to improve the understanding and performance of woodburning stoves. First, it is suggested that different refuelling rates be investigated, focusing on mass-based rather than volume-based refuelling to evaluate their impact on combustion. Lower fuelling rates could result in lower oven temperatures, more suitable for baking or roasting. Uniform wood pellets are recommended to achieve more consistent combustion results. The homogeneity that pellets provide is lacking when using raw wood cuttings.

Adjusting the refuelling rate with the air-inlet opening could help achieve and maintain the power phases described by the testing protocol. Furthermore, testing the wood species in an improved cookstove previously evaluated would provide a more reliable baseline for comparison. Ensuring uniform size between species, despite the hardness of wood, is suggested.

Further research should separate PM_{2.5} and PM₁₀ concentrations, rather than only total suspended particles (TSP), to gain more detailed information on particulate matter emissions. Improving the stove design to minimise inlet air leakages is advised. The air inlet slide position needs markings to indicate power levels related to airflow regulation. While incorporating a small oven is a feature users appreciate, the design needs better adjustment to regulate the oven temperature within an effective baking range (170-220 °C). The stove can also be evaluated as part of a field-based study for real-world use.

Finally, it is recommended that the stove be evaluated to evaluate the performance aligned with the likely end use as per the original design intent, which is using natural twigs rather than geometrically exact pieces of timber sawn from dense trunk wood.

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ANNEXURE A COMMISSIONING RUNS AND STOVE BURN-IN

The NWU stove testing facility has been used since 2014 and primarily focuses on testing a semi-continuous coal stove. Due to the stove's size and operation, the facility had to undergo modifications to test the Flamingo™ stove. The facility was adapted and re-commissioned. The adjustments included the addition of appropriate sampling ports to the chimney and thermocouples within the stove and modifying the diluter to fit the smaller chimney diameter of the Flamingo™ stove. Figure A-1 and Figure A-2 show some of the changes.

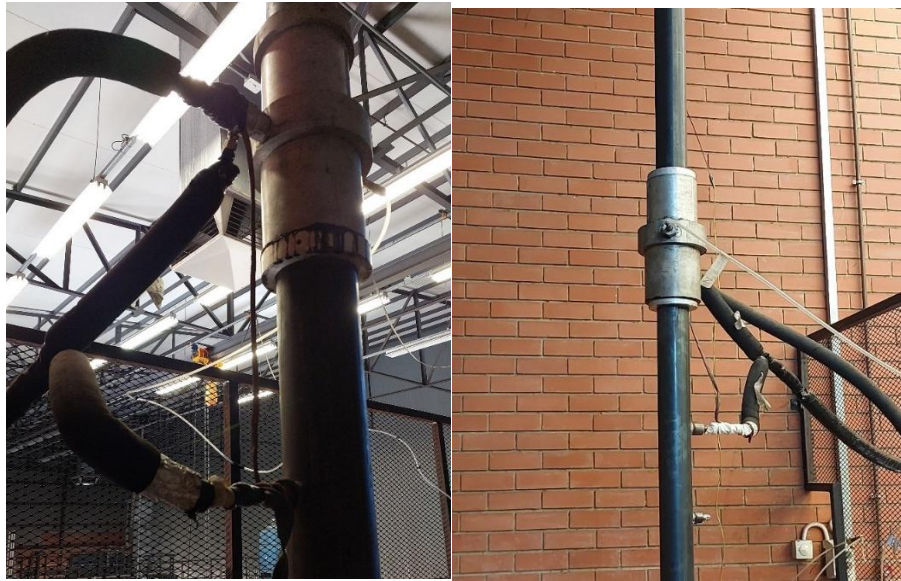


Figure A-1: Diluter is in the coal stove chimney and Flamingo™ chimney.

The diluter was fitted with an adaptor to fit the smaller chimney diameter.



Figure A-2: Thermocouple fittings were placed on the Flamingo™ stove.

Stove burn-in

The Flamingo™ stove was burned in before the emissions monitoring equipment was installed. This was done to establish the stove's operation and familiarise oneself with the HTP and water boiling test. Only one refuelling event was done, adding six wood cuttings at once. Lastly, the correct ignition method was investigated.

The wood size most suitable for the stove was also determined from these sequences. The burn-in runs were conducted using Kameeldoring wood in varied sizes also to determine the appropriate wood diameters for the stove. The sizes tested were 10 x 10 mm, 15 x 15 mm, 20 x 20 mm and 30 x 30 mm. The same mass of wood was used for each size.

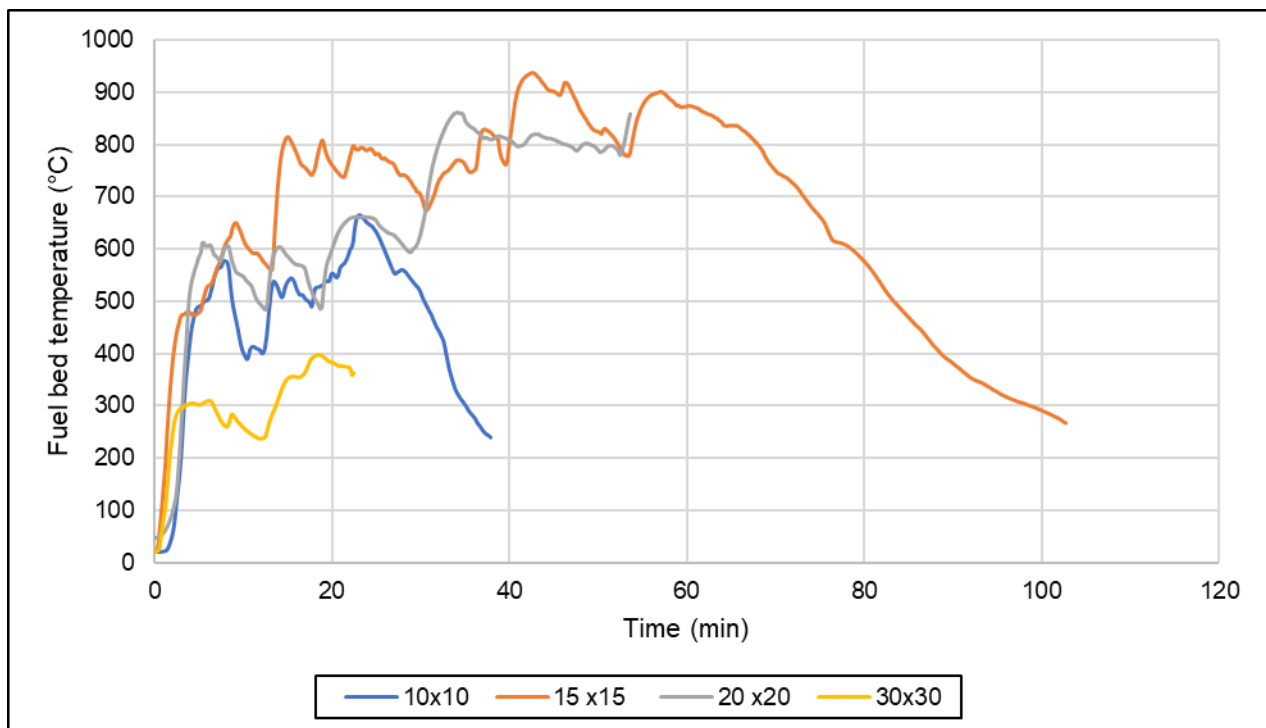


Figure A-3: Fuel bed temperature between four wood sizes.

The smallest size was eliminated due to its quick burn time and subsequent high volume needed for tests. The smallest size tested only burned for ~40 minutes. A longer burn time is required to record adequate emission data for the water heating test. The largest size was also eliminated. Ignition failed twice due to the larger surface area. The 20 minutes of burning time, as seen in Figure A-3, is attributed to the ignition and burning of the kerosene-doused woodchips and kindling. The 20 x 20 mm samples were easier to ignite and burn for longer, but refuelling with bigger pieces extinguished the current fire. The 15 x 15 mm wood cuttings were the easiest to ignite, refuel and burn for an appropriate duration to complete the WHT and emissions monitoring.



Figure A- 4: Burn in of stove, without emissions monitoring.

Overall, ten burn-in runs were conducted, only measuring the temperature and mass data of the stove.

Commissioning runs

Commissioning tests were conducted to determine the experimental parameters that are not included in the standard HTP, such as the refuelling times. The commissioning tests were performed using Black Wattle as fuel.

Three tests, CR-01, CR-02 and CR-03 were conducted. Refuelling was not done on a time-based interval but rather at the instance of a fuel bed temperature drop. Table A-1 indicates that.

Table A-1: Refuelling times for CR-01 to CR-03.

Refuelling times			
Refuelling	Run 1	Run 2	Run 3
Ignition	09:47	08:17	09:01
1	09:52	08:27	09:09
2	10:03	08:36	09:17
3	10:10	08:41	09:25
4	10:18	08:44	09:28
5	10:22	08:47	09:35
6	10:27	08:50	09:49
7	10:30	-	-

Figure A-3 shows the change in fuel bed temperatures over time.

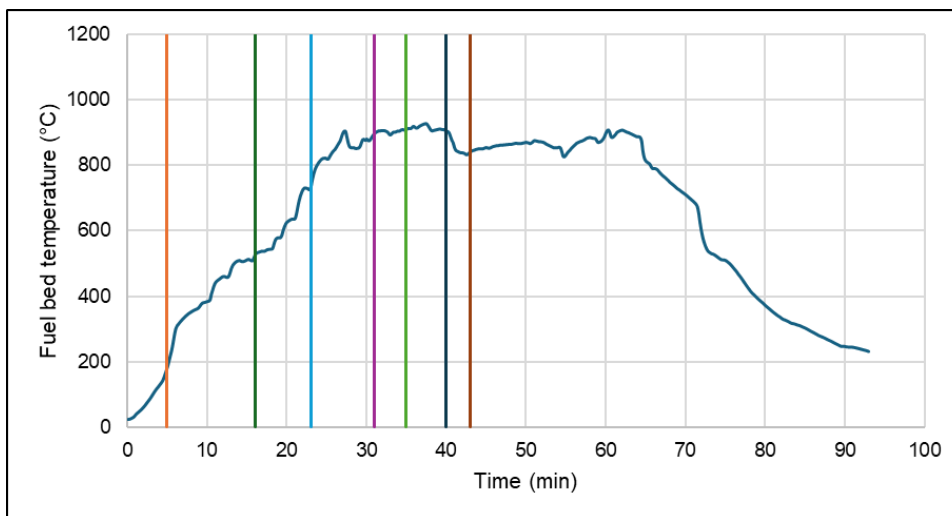


Figure A-5: Fuel bed temperature over time for CR-01.

Longer refuelling times (such as 11 minutes) resulted in the fuel being almost depleted by the time of the next refuelling. In this case, the newly added cutting struggled to ignite due to the lack of a flame. Shorter intervals resulted in the fuel bed being too full, limiting proper airflow around the burning pieces. The placement of the fuel bed thermocouple also caused issues with this procedure. A decrease in temperature would be observed, even if the fuel bed is full and burning correctly, due to ash blocking the thermocouple. From this, it was concluded that refuelling should be done on a time-based interval. The time-based interval also contributed to the quality control of the study by eliminating any variance caused by the refuelling and human error.

Further commissioning tests were conducted using Black Wattle and left for the entire burn sequence. The tests were stopped once the ambient CO concentration was reached and the fuel bed temperature returned to ambient temperature. For these sequences, the refuelling was changed to a time-based interval. No water heating tests were performed during these sequences. Although the test sequences were started with ~900 g of wood, the three test sequences had different burn rates. The burning rates ranged between 9.8-17.9 g/min. The difference between the three sequences could be attributed to the wood's heterogeneous nature or the stove's function. Each run had ten refuelling intervals, and the air inlet was 100% open.

Figure A-6 shows the fuel bed temperature of three complete burning sequences.

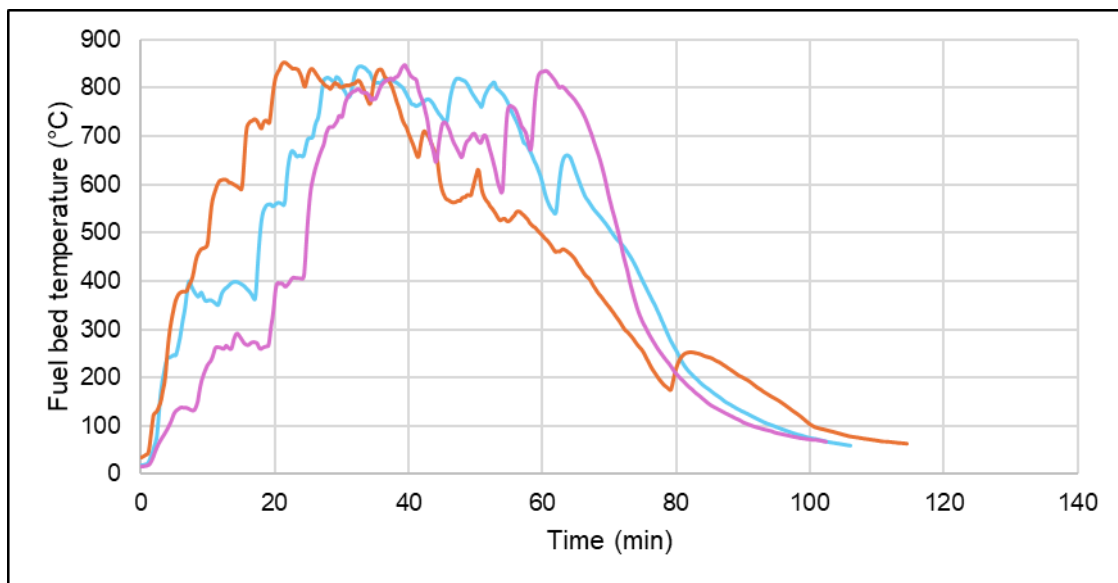


Figure A-6: The fuel bed temperature of the Black Wattle complete burn sequence.

ANNEXURE B DENSITY CALCULATIONS AND CORRELATIONS

Table B-1 shows each species' mass and volume details as determined for use in density calculations.

Table B-1: Mass and volume details of cuttings for determining density.

Sickle Bush	Mass (g)	W (mm)	H (mm)	L (cm)	Volume (cm ³)	Mass (kg)	Density (g/cm ³)	Density (kg/m ³)	Average
	82.09	14.5	12.5	27.7	50.21	0.08	1.64	1 635	1 307
	55.38	14.9	14.9	27.5	61.05	0.06	0.91	907	
	72.83	14	14.5	27.5	55.83	0.07	1.30	1 305	
	79.43	12	15	27.8	50.04	0.08	1.59	1 587	
	79.64	17	18	23.6	72.22	0.08	1.10	1 103	
Mopane	Mass (g)	W (mm)	H (mm)	L (cm)	Volume (cm ³)	Mass (kg)	Density (g/cm ³)	Density (kg/m ³)	Average
	68.02	13.9	14	25.8	50.2	0.1	1.4	1 355	1 415
	83.75	14	15	25.3	53.1	0.1	1.6	1 576	
	56.34	13	14	25.5	46.4	0.1	1.2	1 214	
	59.77	10	14.5	25.6	37.1	0.1	1.6	1 610	
	57.4	13	13	25.7	43.4	0.1	1.3	1 322	
Leadwood	Mass (g)	W (mm)	H (mm)	L (cm)	Volume (cm ³)	Mass (kg)	Density (g/cm ³)	Density (kg/m ³)	Average
	88.21	17.5	16	23.3	65.2	0.1	1.4		1 466
	108.8	17	17	25.8	74.6	0.1	1.5	1 459	
	93.87	16	17	25.9	70.4	0.1	1.3	1 332	
	116.5	17.1	17	23.3	67.7	0.1	1.7	1 720	
	108.2	17	17	25.5	73.7	0.1	1.5	1 468	
Black Wattle	Mass (g)	W (mm)	H (mm)	L (cm)	Volume (cm ³)	Mass (kg)	Density (g/cm ³)	Density (kg/m ³)	Average
	87.52	17.5	17	27	80.3	0.1	1.1	1 090	993
	67.93	15	17.5	27	70.9	0.1	1.0	958	
	65.44	17	17	23.4	67.6	0.1	1.0	968	
	57.76	16	17	23.3	63.4	0.1	0.9	911	
	58.28	16	15	23.4	56.2	0.1	1.0	1 038	

A trend was observed between the density and the burn rate, showing that a higher density results in a slower burn rate. Figure B-1 shows this.

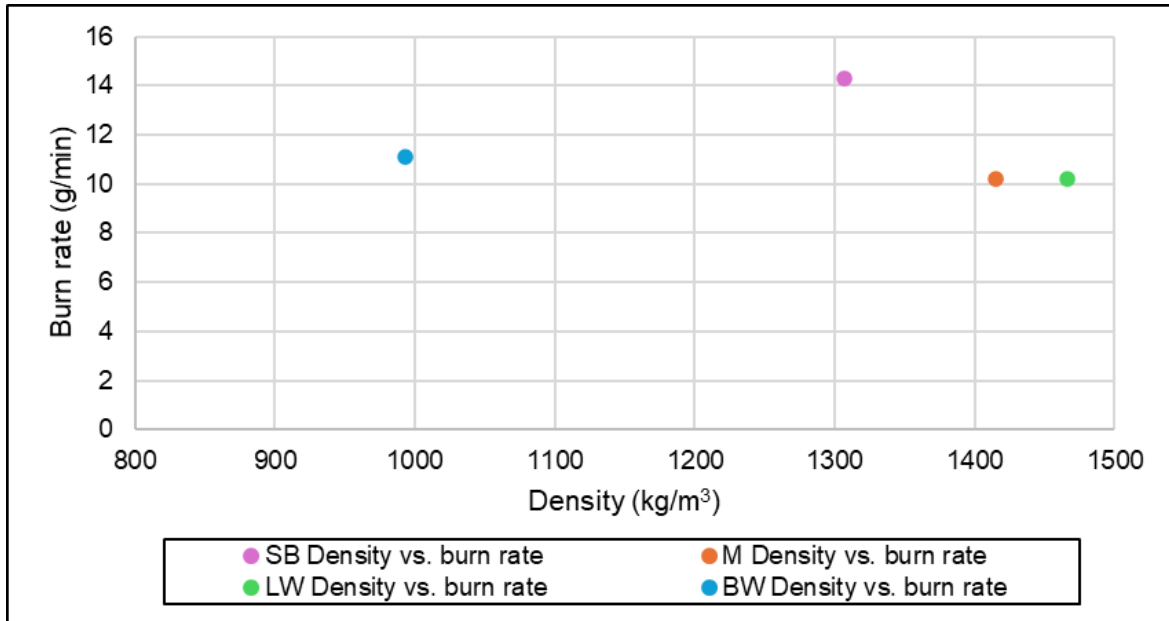


Figure B-1: Density vs. burn rate of each species.

ANNEXURE C WATER FRACTION CALCULATION

Water, as a product of combustion, as well as the inherent moisture contained in wood, is released in the flue gas of the stove. The instruments in the NWU testing facility cannot measure the water vapour in the flue gas. Hence, an approximation is determined from the ultimate analysis of the wood. The molar ratio between water and carbon is calculated as follows:

For one kilogram of wood, the mass of each component in the wood is calculated.

$$1000 [g] \cdot wt\%_{carbon} = m_{carbon} [g] \quad C-1$$

The mass is converted to moles using the molar mass of each component.

The mol of water produced is calculated from the hydrogen content of the wood, as well as the inherent moisture content. The total moles of water produced are divided by the total moles of carbon to determine the molar ratio.

$$\frac{n_{H_2O}}{n_C} = H_2O \text{ ratio} \quad C-2$$

For 1 kg of wood:				
SB		g	g/mol	mol
		1000		
% C	52.4	524.3	12	43.69
% H	6.7	66.9	1	66.92
% N	0.5	5.4	14	0.39
% S	0.1	0.9	32	0.03
% O*	40.2	402.4	16	25.15
H ₂ O	6.70	67	18	3.72

Ratio	H ₂ O	C
From H	33.5	43.7
From H ₂ O	3.72	

ratio H ₂ O	0.85 mol H ₂ O/mol C
------------------------	---------------------------------

Figure C-1: Example calculation of the ratio between carbon and water.

The water and carbon ratios determine the water fraction for each data point during a test sequence by relating the water to CO and CO₂. The ratio is multiplied by the sum of the molar fractions of the two.

$$y_{H_2O} = H_2O \text{ ratio} \cdot (y_{CO_2} + y_{CO}) \quad \text{C-3}$$

The water fraction is used to calculate the chimney's volumetric flow rate and the flue gas flow rate and directly influences the calculation of the PM flow rate. It is necessary to account for the water fraction since the measurements are taken on a dry basis.

Table C-1 shows the water ratios for each species.

Table C-1: Water ratio of each species.

Water ratio	
Sickle Bush	0.85
Mopane	0.83
Leadwood	0.86
Black Wattle	0.74

ANNEXURE D CARBON BALANCE AND EXAMPLE CALCULATION

The calculation of the emission factors was done using a carbon balance, as discussed in Chapter 4.5.2. The following example is based on a test sequence using Sickie Bush without using the oven.

Before data processing can be done, the mass data is cleaned manually, by removing any peaks caused by moving pots or refuelling, and smoothing using a moving average. The difference between the raw and cleaned mass curves is shown in Figure D-1.

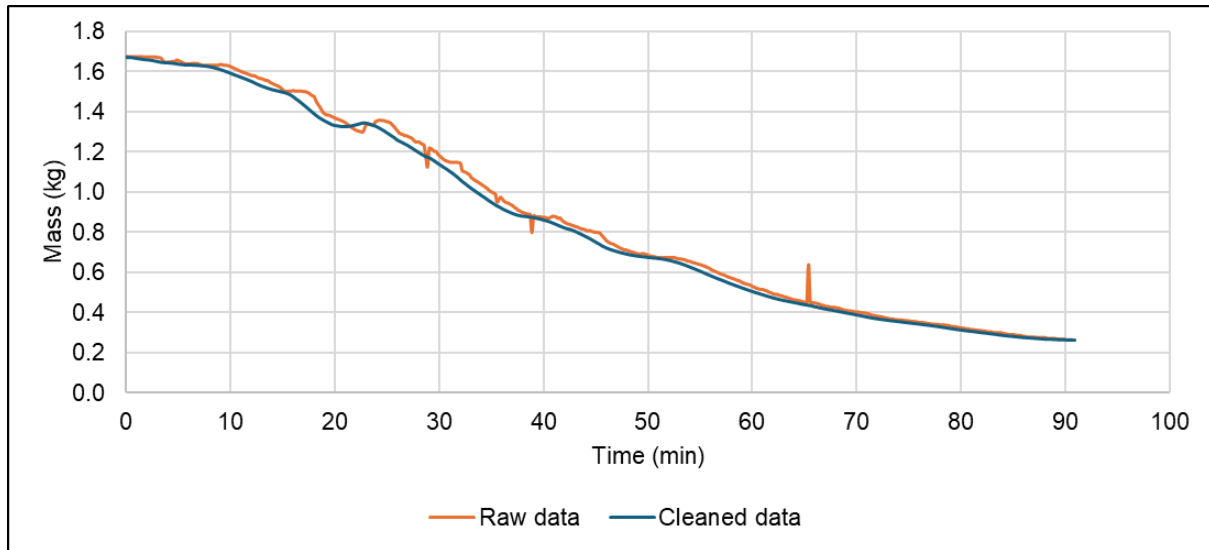


Figure D-1: Data cleaning.

Firstly, the mass loss rate of the fuelwood is determined ($\dot{m}_{burn} \left[\frac{g}{min} \right]$) by using the mass recording every 10 seconds (Figure D-2).

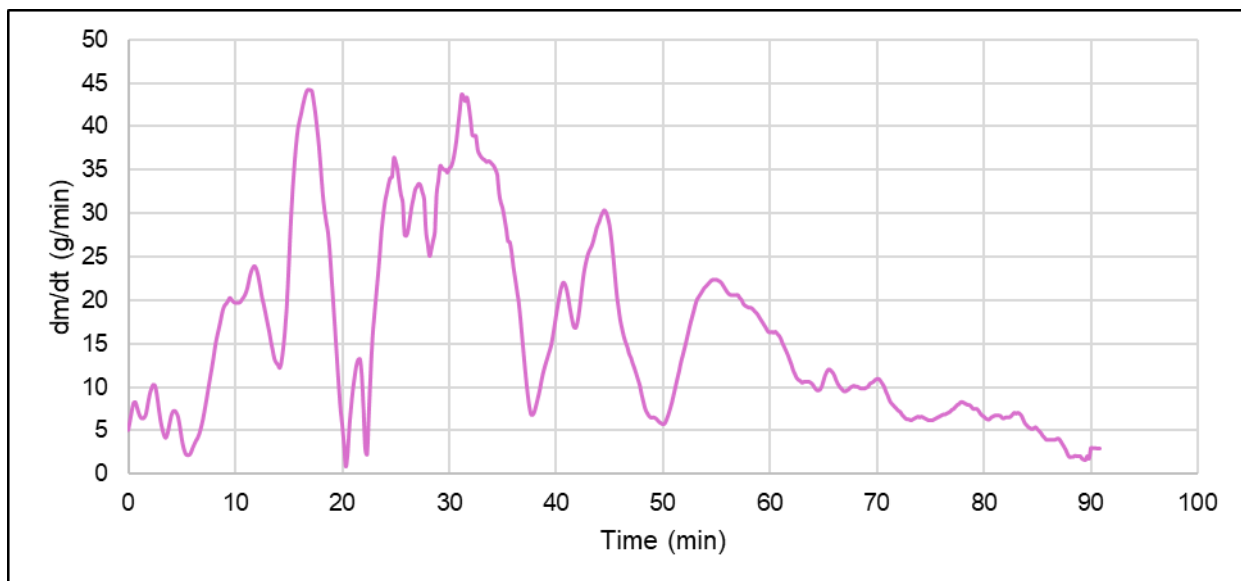


Figure D-2: The mass loss rate of the fuelwood in g/min.

From the above data, only carbon's mass loss rate is calculated using the %C from the ultimate analysis (Figure D-3).

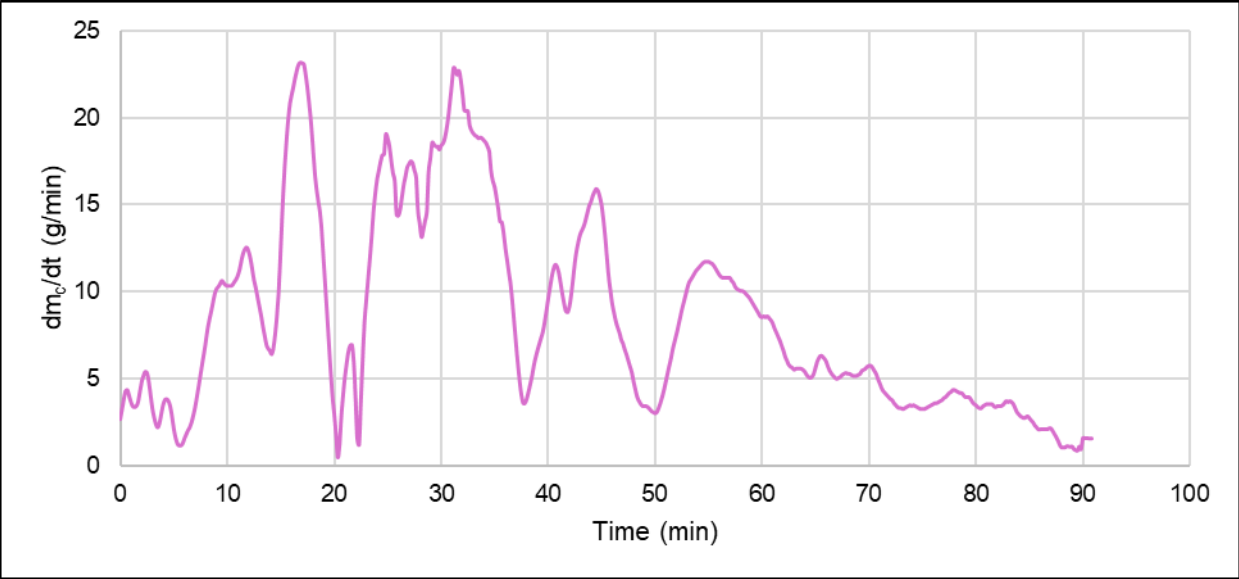


Figure D-3: Carbon mass loss rate in g/min.

The mass loss rate is converted to a molar rate (Figure D-4).

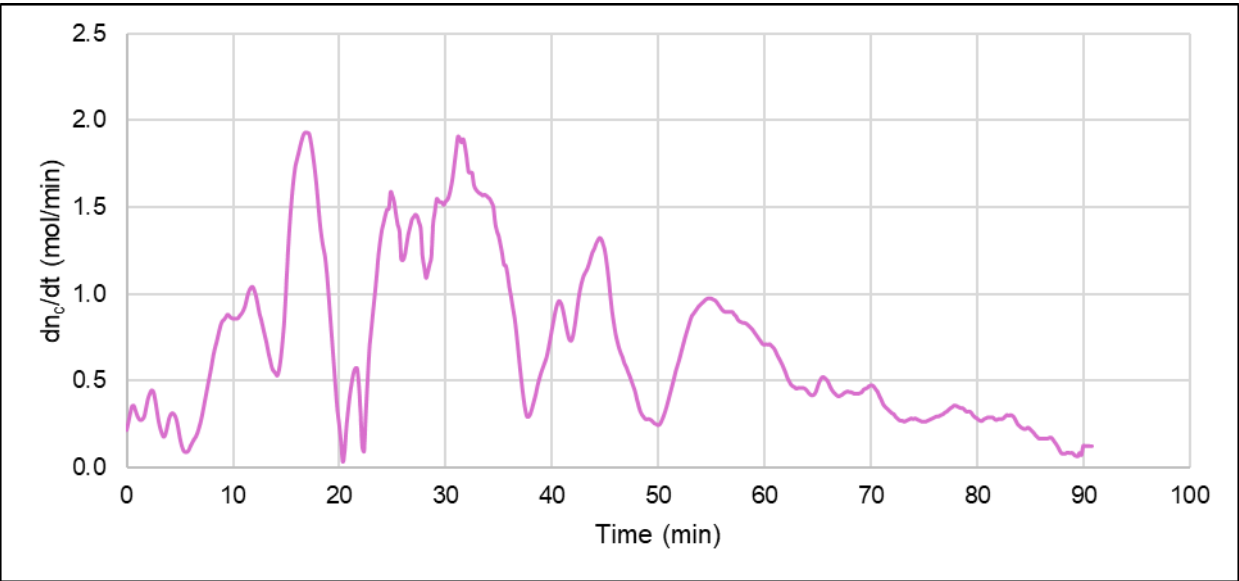


Figure D-4: Molar rate of carbon.

The flue gas molar flow rate was then calculated by relating the CO and CO₂ concentrations, carbon flow rate, and moisture fraction (Figure D-5).

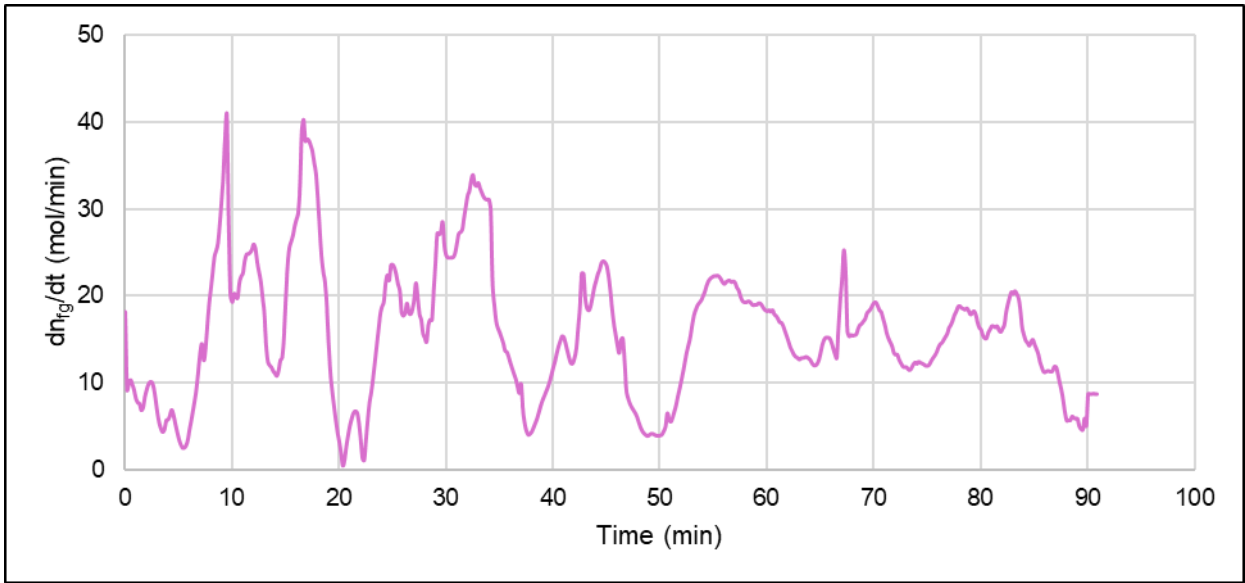


Figure D-5: Flue gas flow rate in mol/min.

The flue gas flow rate is used to calculate the molar flow rate of each component in the flue gas (Figure D-6 and Figure D-7).

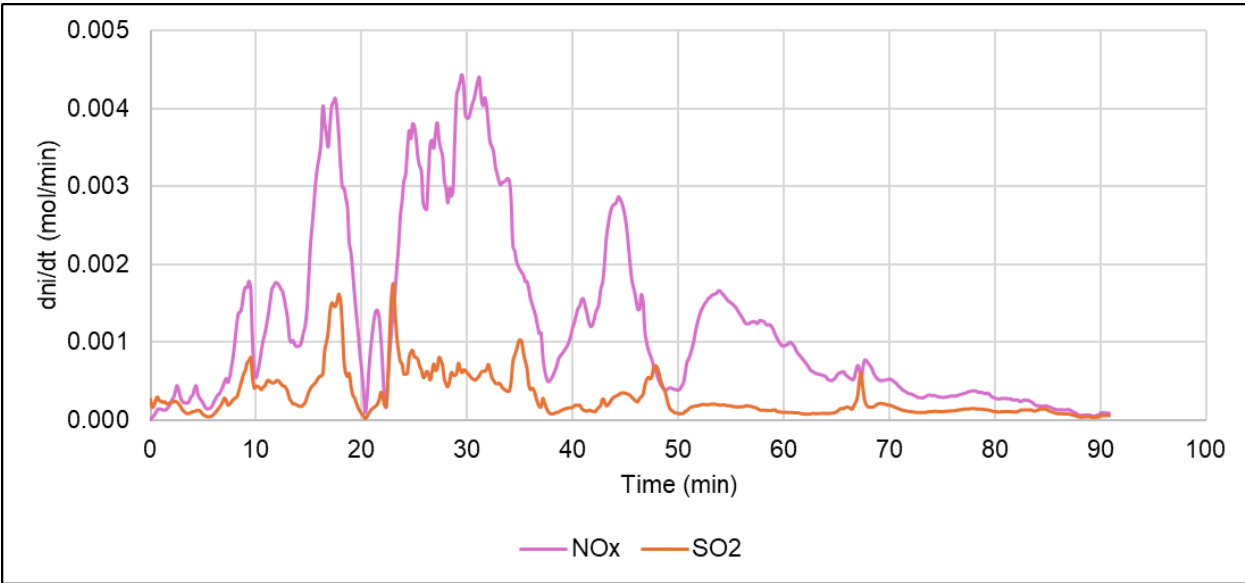


Figure D-6: Molar flow rate of SO₂ and NO_x in mol/min.

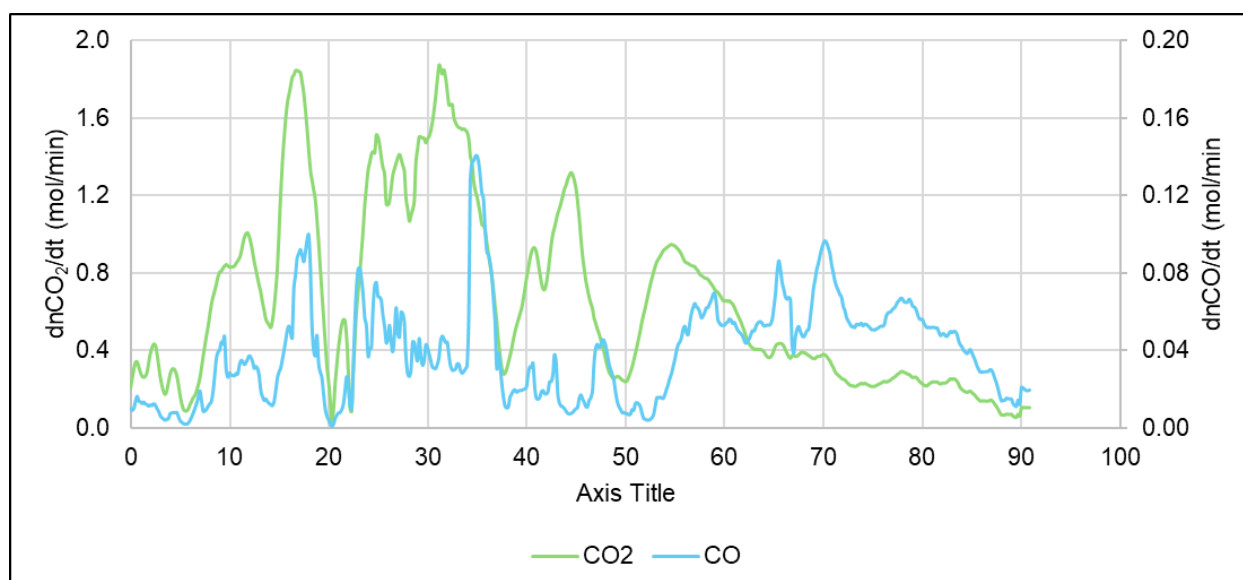


Figure D-7: Molar flow rate of CO₂ and CO in mol/min.

The molar flow rate is then converted to a mass flow rate for each component.

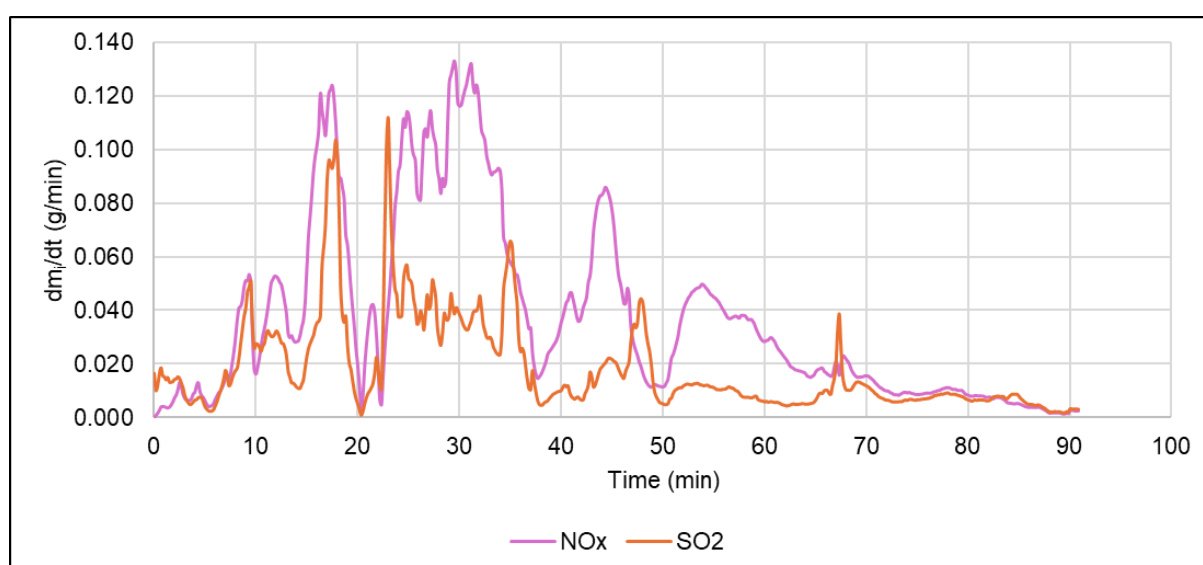


Figure D-8: Mass flow rate of NO_x and SO₂ in g/min.

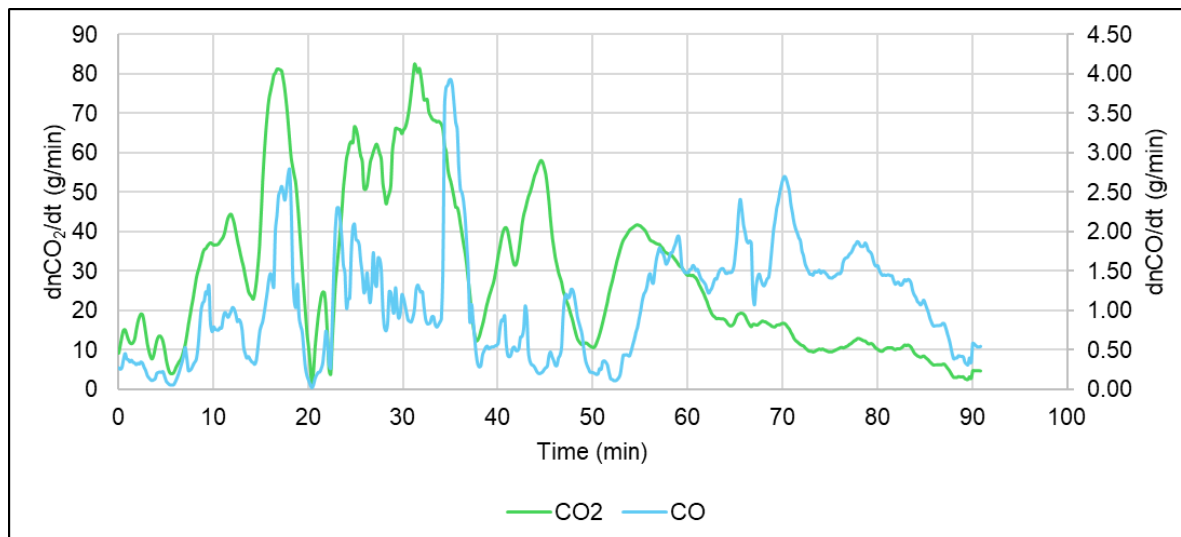


Figure D-9: Mass flow rate of CO₂ and CO in g/min.

The average volumetric flow rate is also calculated to calculate the mass flow rate as part of the PM emission factor calculation.

Table D-1: Volumetric flow rate for Sickle Bush test sequence.

		Sickle Bush
Average vol. flow rate	m ³ /min	0.6

Figure D-10 shows the mass flow rate of the PM as calculated.

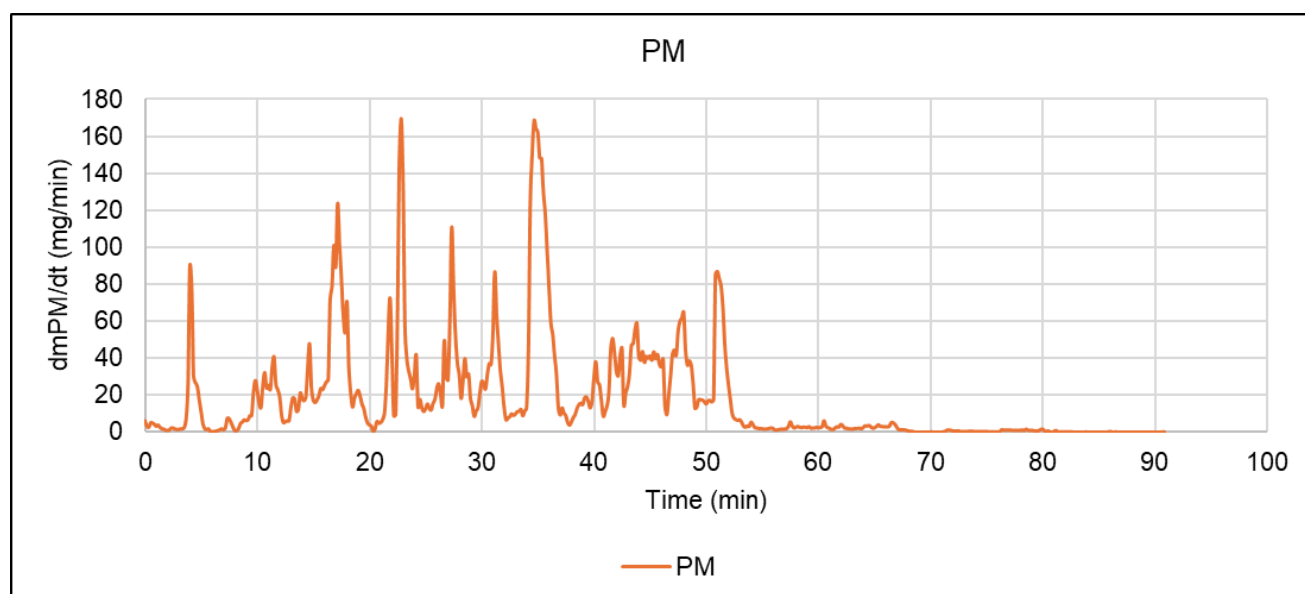


Figure D-10: Mass flow rate of PM from a Sickle Bush test sequence.

The above graphs are integrated to determine the mass of each pollutant emitted using MATLAB. The following script was used to determine the mass of each pollutant released.

```
data = readtable('SB, NO 1 EF integrate.xlsx');

Time = data.Time;
colA = data.NO;
colB = data.SO2;
colC = data.CO2;
colD = data.CO;
colE = data.PM;

integralA = trapz(time, colA);
integralB = trapz(time, colB);
integralC = trapz(time, colC);
integralD = trapz(time, colD);
integraleE = trapz(time, colE);

fprintf('Integral of column A over time: %f\n', integralA);
fprintf('Integral of column B over time: %f\n', integralB);
fprintf('Integral of column C over time: %f\n', integralC);
fprintf('Integral of column D over time: %f\n', integralD);
fprintf('Integral of column E over time: %f\n', integraleE);
```

Table D-1 shows the mass (g) output given by Matlab.

Table D-2: Matlab output.

Integral of column A over time: 3.375663	NO
Integral of column B over time: 1.662455	SO ₂
Integral of column C over time: 2615.816382	CO ₂
Integral of column D over time: 100.313394	CO
Integral of column E over time: 1222.612896	PM

The emission factors are then calculated by dividing the mass value for each pollutant by the mass and LHV, as seen in Equation 4-15.

As a validation method, the compounds recovered from the fuel are determined from the measured CO, CO₂, SO₂ and NO concentrations. The elements remaining in the ash are excluded.

Firstly, Equation D-1 is used to determine the mass of each element in the wood burned from the ultimate analysis.

$$m_i = m_{T,f} \cdot x_i \quad (\text{D-1})$$

where m_i [g] is the mass of each element, and x_i [wt%] is the percentage determined during the ultimate analysis.

The percentage of each element in the compounds is determined using the molar weights of each compound (Equation D-2).

$$EC = \frac{MW_{element}}{MW_{comp}} \cdot 100 \quad (D-2)$$

Lastly, the mass of each element from the compounds is determined (Equation D-3).

$$m_j = m_i \cdot EC \quad (D-3)$$

where m_j [g] is the mass of each element recovered from the flue gas. An example calculation is shown in Table D-3.

Table D-3: Example calculation for a Sickle Bush test sequence.

Sickle Bush		
Mass of fuel burnt	1414.0	g
C in	741.4	g
N in	7.7	g
S in	1.3	g
C in CO	0.4	%
C in CO ₂	0.3	%
N in NO	0.5	%
S in SO ₂	0.5	%
CO ₂	2614.0	g
CO	100.0	g
NO	3.4	g
SO ₂	1.7	g
C out	755.8	g
N out	1.6	g
S out	0.8	g
C recovered	102	%
N recovered	21	%
S recovered	66	%

The recovery of carbon, nitrogen and sulphur over a combustion experiment is summarised in Table D-4.

Table D-4: Percentage recovery of carbon, nitrogen and sulphur.

Species	Recovery (%)		
	C	N	S
Sickle Bush	102	21	66
Mopane	99	17	75
Leadwood	98	23	38
Black Wattle	96	4	67

Acceptable recovery is observed for carbon. Low recovery rates are observed for nitrogen and sulphur. The assumption that the carbon reacts completely and is released as either CO or CO₂ thus stands. The recovery does show that nitrogen and sulphur escape in different chemical forms than NO_x and SO₂.

ANNEXURE E EXPERIMENTAL UNCERTAINTY

The experimental sequences were repeated in triplicate to determine the experimental uncertainty. The uncertainty analysis below is based on repeats using Sickie Bush as fuelwood without using the oven.

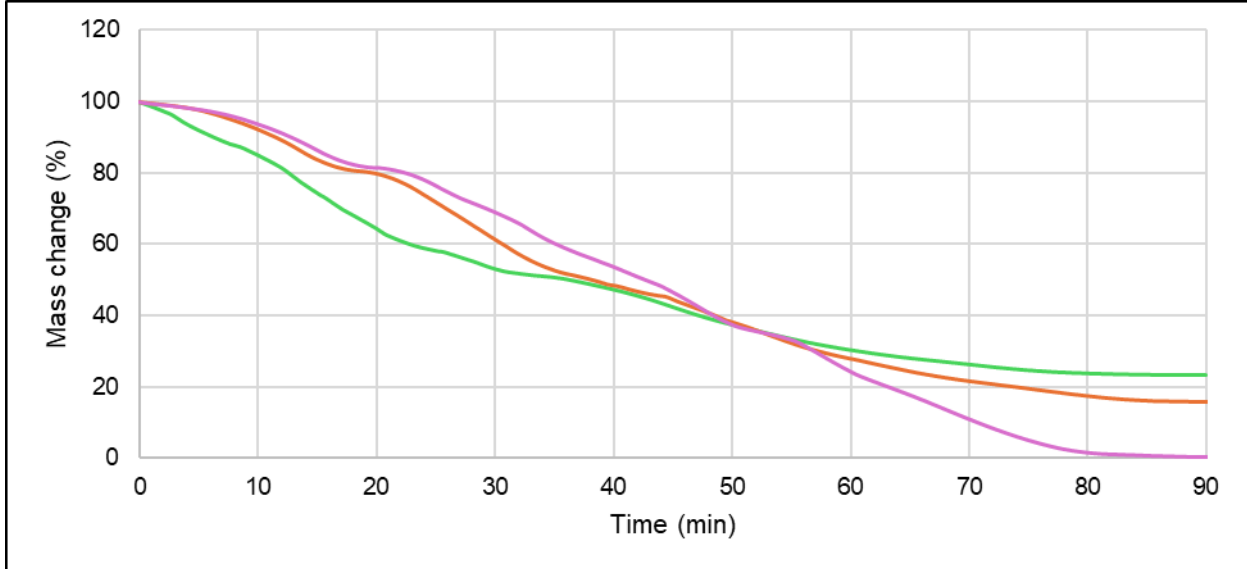


Figure E-1: The mass change of three experimental sequences.

Two runs showed a similar mass loss rate, with one burning quicker towards the end. This run also burnt more wood, although the three had approximately the same fuel mass at the start. Table E-1 shows the uncertainty analysis for all the key performance parameters for Sickie Bush.

The mean between three runs, the standard deviation and the 95% confidence interval for the mean are shown. The width of the confidence interval is acceptable due to good repeatability between the experimental runs and low standard deviation. Slight variations occur, due to the heterogeneity of raw wood cuttings.

The confidence interval was calculated as follows:

$$CI = \bar{x} \pm t\left(\frac{\alpha}{2}, n - 1\right) \frac{S}{\sqrt{n}} \quad (3-21)$$

where $\bar{x}$ is the mean value, $t\left(\frac{\alpha}{2}, n - 1\right)$ is the quantile from the t-distribution at a significance level of α (0.05 for 95% CI), S is the standard deviation of a sample and n is the number of runs.

Table E-1: Sickie Bush uncertainty analysis.

	Sickie Bush Uncertainty Analysis								
	Measurements			Mean	Standard deviation	Standard error of the mean	95% Margin of Error	95% Confidence Interval	
Power (kW)	4.8	3.4	4.1	4.1	0.7	0.4	1.8	2.3	5.8
Burn rate (g/min)	15.6	13.6	13.4	14.2	1.2	0.7	3.0	11.2	17.2
Volumetric flow rate (m ³ /hr)	0.6	0.43	0.52	0.5	0.1	0.0	0.2	0.3	0.7
NO _x EF (g/MJ)	0.13	0.13	0.12	0.13	0.0	0.0	0.0	0.11	0.14
SO ₂ EF (g/MJ)	0.08	0.02	0.06	0.06	0.0	0.0	0.1	0.00	0.13
CO ₂ EF (g/MJ)	94	89	91	91	2.5	1.5	6.3	85	98
CO EF (g/MJ)	3.6	4.4	4.3	4.10	0.4	0.3	1.1	3.02	5.18
CO/CO ₂ (g/MJ)	0.0	0.0	0.0	0.04	0.0	0.0	0.0	0.03	0.06
PM EF (g/MJ)	0.06	0.10	0.16	0.11	0.0	0.0	0.1	0.00	0.22
Thermal efficiency in primary pot (%)									
Phase 1	5.8	19.9	13.7	13.2	7.1	4.1	17.6	0.0	30.8
Phase 2	7.7	10.2	10.3	9.4	1.5	0.8	3.6	5.8	13.0
Phase 3	8.8	10.9	7.3	9.0	1.8	1.1	4.5	4.5	13.5
Thermal efficiency in secondary pot (%)									
Phase 1	4.6	9.9	10.5	8.3	3.2	1.9	8.1	0.3	16.4
Phase 2	5.0	6.8	6.4	6.1	0.9	0.5	2.3	3.7	8.4
Phase 3	5.6	2.9	2.2	3.6	1.8	1.0	4.5	0.0	8.1
Effective thermal efficiency (%)									
Phase 1	10.4	29.8	24.2	21.5	10.0	5.8	24.8	0.0	46.3
Phase 2	12.7	17.1	16.7	15.5	2.4	1.4	5.9	9.6	21.4
Phase 3	14.4	13.8	9.4	12.6	2.7	1.6	6.7	5.8	19.3
Fuel burned (g)									
Phase 1	194	220	90	167.8	68.7	39.7	170.7	0.0	338.5
Phase 2	175	127	168	156.5	25.8	14.9	64.0	92.5	220.5
Phase 3	180	14	160	117.9	90.9	52.5	225.9	0.0	343.8
Duration (min)									
Phase 1	8.0	8.3	8.0	8.1	0.2	0.1	0.5	7.6	8.6
Phase 2	9.3	10.0	12.2	10.5	1.5	0.9	3.7	6.8	14.2
Phase 3	10.0	10.2	14.5	11.6	2.6	1.5	6.3	5.2	17.9
Firepower (kW)									
Phase 1	7.1	7.7	3.3	6.0	2.4	1.4	6.0	0.1	12.0
Phase 2	5.5	3.7	4.1	4.4	0.9	0.5	2.3	2.1	6.7
Phase 3	5.3	0.4	3.2	3.0	2.5	1.4	6.1	0.0	9.1
Max fuel bed temperature (°C)									
Phase 1	870	837	879	862.0	22.1	12.8	54.9	807.1	916.9
Phase 2	888	898	907	897.7	9.5	5.5	23.6	874.1	921.3
Phase 3	812	890	868	856.7	40.2	23.2	99.9	756.8	956.6
SFC (g/l)									
Phase 1	0.12	0.14	0.06	0.10	0.0	0.0	0.1	0.00	0.21
Phase 2	0.11	0.08	0.11	0.10	0.0	0.0	0.0	0.06	0.14
Phase 3	0.11	0.01	0.10	0.07	0.1	0.0	0.1	0.00	0.21

Table E-2: Mopane uncertainty analysis.

	Mopane Uncertainty Analysis								
	Measurements			Mean	Standard deviation	Standard error of the mean	95% Margin of Error	95% Confidence Interval	
Power (kW)	3.3	3.2	2.7	3.1	0.3	0.2	0.7	2.3	3.8
Burn rate (g/min)	10.9	10.7	9.1	10.2	1.0	0.6	2.5	7.8	12.7
Volumetric flow rate (m ³ /hr)	1.0	0.55	0.49	0.7	0.3	0.2	0.7	0.0	1.4
NO _x EF (g/MJ)	0.07	0.08	0.09	0.08	0.0	0.0	0.0	0.06	0.10
SO ₂ EF (g/MJ)	0.07	0.26	0.06	0.13	0.1	0.1	0.3	0.00	0.41
CO ₂ EF (g/MJ)	95	94	95	95	0.4	0.2	1.0	94	96
CO EF (g/MJ)	2.7	3.5	3.2	3.14	0.4	0.2	1.0	2.18	4.09
CO/CO ₂ (g/MJ)	0.0	0.0	0.0	0.03	0.0	0.0	0.0	0.02	0.04
PM EF (g/MJ)	0.11	0.11	0.10	0.11	0.0	0.0	0.0	0.09	0.12
Thermal efficiency in primary pot (%)									
Phase 1	5.7	8.9	7.6	7.4	1.6	0.9	4.0	3.3	11.4
Phase 2	15.7	12.0	9.6	12.4	3.1	1.8	7.7	4.8	20.1
Phase 3	11.2	10.2	14.3	11.9	2.1	1.2	5.2	6.6	17.1
Thermal efficiency in secondary pot (%)									
Phase 1	1.3	3.7	2.8	2.6	1.2	0.7	2.9	0.0	5.5
Phase 2	3.4	6.3	2.3	4.0	2.0	1.2	5.1	0.0	9.1
Phase 3	7.3	6.0	8.3	7.2	1.2	0.7	2.9	4.3	10.1
Effective thermal efficiency (%)									
Phase 1	7.0	12.5	10.4	10.0	2.8	1.6	7.0	3.0	17.0
Phase 2	19.2	18.3	11.9	16.5	3.9	2.3	9.8	6.7	26.3
Phase 3	18.5	16.2	22.5	19.1	3.2	1.8	8.0	11.1	27.0
Fuel burned (g)									
Phase 1	250	191	234	225.2	30.6	17.7	76.0	149.2	301.2
Phase 2	147	147	178	157.7	18.0	10.4	44.7	113.0	202.4
Phase 3	144	155	111	136.8	23.0	13.3	57.2	79.6	194.0
Duration (min)									
Phase 1	15.0	10.7	18.2	14.6	3.8	2.2	9.4	5.3	24.0
Phase 2	15.3	15.7	18.0	16.3	1.5	0.8	3.6	12.7	19.9
Phase 3	22.0	31.3	20.7	24.7	5.8	3.4	14.4	10.2	39.1
Firepower (kW)									
Phase 1	4.9	5.3	3.8	4.6	0.8	0.4	1.9	2.7	6.5
Phase 2	2.8	2.8	2.9	2.8	0.1	0.0	0.2	2.6	3.0
Phase 3	1.9	1.5	1.6	1.7	0.2	0.1	0.6	1.0	2.3
Max fuel bed temperature (°C)									
Phase 1	762	817	776.4	785.1	28.5	16.5	70.9	714.3	856.0
Phase 2	762	820	862	814.7	50.2	29.0	124.7	689.9	939.4
Phase 3	662.3	733.8	795.9	730.7	66.9	38.6	166.1	564.6	896.7
SFC (g/l)									
Phase 1	0.16	0.12	0.15	0.14	0.0	0.0	0.0	0.09	0.19
Phase 2	0.09	0.09	0.11	0.10	0.0	0.0	0.0	0.07	0.13
Phase 3	0.09	0.10	0.07	0.09	0.0	0.0	0.0	0.05	0.12

Table E-3: Leadwood uncertainty analysis.

	Leadwood Uncertainty Analysis								
	Measurements			Mean	Standard deviation	Standard error of the mean	95% Margin of Error	95% Confidence Interval	
Power (kW)	2.7	2.5	3.1	2.8	0.3	0.2	0.8	2.0	3.5
Burn rate (g/min)	9.9	9.2	11.4	10.2	1.1	0.6	2.8	7.4	13.0
Volumetric flow rate (m ³ /hr)	0.4	0.41	0.47	0.4	0.1	0.0	0.1	0.3	0.5
NO _x EF (g/MJ)	0.07	0.08	0.08	0.08	0.0	0.0	0.0	0.06	0.09
SO ₂ EF (g/MJ)	0.04	0.05	0.03	0.04	0.0	0.0	0.0	0.02	0.06
CO ₂ EF (g/MJ)	101	107	101	103	3.5	2.0	8.6	94	112
CO EF (g/MJ)	3.3	3.5	2.7	3.17	0.4	0.2	1.0	2.13	4.20
CO/CO ₂ (g/MJ)	0.0	0.0	0.0	0.03	0.0	0.0	0.0	0.02	0.04
PMEF (g/MJ)	0.10	0.10	0.10	0.10	0.0	0.0	0.0	0.10	0.10
Thermal efficiency in primary pot (%)									
Phase 1	7.7	7.1	10.7	8.5	1.9	1.1	4.8	3.8	13.3
Phase 2	12.0	12.2	10.8	11.7	0.7	0.4	1.8	9.8	13.5
Phase 3	17.2	19.2	12.0	16.1	3.7	2.1	9.2	7.0	25.3
Thermal efficiency in secondary pot (%)									
Phase 1	3.2	4.9	6.1	4.7	1.4	0.8	3.5	1.2	8.3
Phase 2	4.4	5.2	6.7	5.4	1.1	0.7	2.8	2.6	8.2
Phase 3	9.0	13.3	5.6	9.3	3.8	2.2	9.5	0.0	18.8
Effective thermal efficiency (%)									
Phase 1	11.0	12.0	16.8	13.3	3.1	1.8	7.7	5.6	20.9
Phase 2	16.4	17.4	17.5	17.1	0.6	0.4	1.5	15.6	18.6
Phase 3	26.2	32.5	17.6	25.4	7.4	4.3	18.5	6.9	43.9
Fuel burned (g)									
Phase 1	236	270	179	228.4	46.1	26.6	114.4	113.9	342.8
Phase 2	172	162	182	172.1	10.1	5.8	25.2	146.9	197.2
Phase 3	125	98	162	128.3	32.1	18.5	79.8	48.6	208.1
Duration (min)									
Phase 1	12.7	14.5	13.0	13.4	1.0	0.6	2.4	11.0	15.8
Phase 2	15.0	12.2	16.3	14.5	2.1	1.2	5.3	9.2	19.8
Phase 3	20.7	23.2	14.7	19.5	4.4	2.5	10.9	8.6	30.4
Firepower (kW)									
Phase 1	5.5	5.5	4.0	5.0	0.8	0.5	2.0	2.9	7.0
Phase 2	3.4	3.9	3.3	3.5	0.3	0.2	0.9	2.7	4.4
Phase 3	1.8	1.2	3.2	2.1	1.0	0.6	2.6	0.0	4.7
Max fuel bed temperature (°C)									
Phase 1	736.2	777	728.9	747.4	25.9	15.0	64.4	683.0	811.8
Phase 2	744.1	777.9	744.1	755.4	19.5	11.3	48.5	706.9	803.8
Phase 3	742.8	758.4	742.8	748.0	9.0	5.2	22.4	725.6	770.4
SFC (g/l)									
Phase 1	0.15	0.17	0.11	0.14	0.0	0.0	0.1	0.07	0.21
Phase 2	0.11	0.10	0.11	0.11	0.0	0.0	0.0	0.09	0.12
Phase 3	0.08	0.06	0.10	0.08	0.0	0.0	0.0	0.03	0.13

Table E-4: Black Wattle uncertainty analysis.

	Black Wattle Uncertainty Analysis								
	Measurements			Mean	Standard deviation	Standard error of the mean	95% Margin of Error	95% Confidence Interval	
Power (kW)	3.6	2.7	3.1	3.1	0.5	0.3	1.1	2.0	4.2
Burn rate (g/min)	12.2	9.1	11.9	11.1	1.7	1.0	4.3	6.8	15.4
Volumetric flow rate (m ³ /hr)	1.6	0.39	0.8	0.9	0.6	0.3	1.5	0.0	2.4
NO _x EF (g/MJ)	0.07	0.11	0.08	0.08	0.0	0.0	0.1	0.03	0.14
SO ₂ EF (g/MJ)	0.04	0.05	0.03	0.04	0.0	0.0	0.0	0.02	0.06
CO ₂ EF (g/MJ)	93	95	94	94	1.3	0.7	3.1	91	97
CO EF (g/MJ)	3.1	3.6	2.5	3.08	0.6	0.3	1.4	1.70	4.45
CO/CO ₂ (g/MJ)	0.0	0.0	0.0	0.03	0.0	0.0	0.0	0.02	0.05
PM EF (g/MJ)	0.07	0.05	0.05	0.06	0.0	0.0	0.0	0.03	0.09
Thermal efficiency in primary pot (%)									
Phase 1	7.7	7.7	10.7	8.7	1.7	1.0	4.3	4.4	13.0
Phase 2	12.0	14.6	10.8	12.5	1.9	1.1	4.8	7.7	17.2
Phase 3	17.2	21.6	12.0	16.9	4.8	2.8	11.9	5.1	28.8
Thermal efficiency in secondary pot (%)									
Phase 1	3.2	4.3	6.1	4.5	1.4	0.8	3.6	1.0	8.1
Phase 2	4.4	7.2	6.7	6.1	1.5	0.8	3.6	2.5	9.7
Phase 3	9.0	13.1	5.6	9.2	3.7	2.2	9.3	0.0	18.5
Effective thermal efficiency (%)									
Phase 1	11.0	12.0	16.8	13.2	3.1	1.8	7.7	5.5	21.0
Phase 2	16.4	21.7	17.5	18.5	2.8	1.6	7.0	11.5	25.5
Phase 3	26.2	34.7	17.6	26.2	8.5	4.9	21.2	5.0	47.3
Fuel burned (g)									
Phase 1	223	233	220	225.6	6.6	3.8	16.4	209.2	242.0
Phase 2	160	128	135	140.8	17.1	9.8	42.4	98.4	183.2
Phase 3	121	85	214	139.8	66.5	38.4	165.2	0.0	305.0
Duration (min)									
Phase 1	12.3	14.8	12.5	13.2	1.4	0.8	3.5	9.8	16.7
Phase 2	13.7	11.7	12.0	12.4	1.1	0.6	2.7	9.8	15.1
Phase 3	16.3	11.2	17.8	15.1	3.5	2.0	8.7	6.4	23.8
Firepower (kW)									
Phase 1	5.3	4.6	5.2	5.0	0.4	0.2	0.9	4.1	6.0
Phase 2	3.4	3.2	3.3	3.3	0.1	0.1	0.3	3.0	3.6
Phase 3	2.2	2.2	3.5	2.6	0.8	0.4	1.9	0.7	4.5
Max fuel bed temperature (°C)									
Phase 1	845	777.3	837	819.8	37.0	21.4	91.9	727.9	911.7
Phase 2	849	747.6	899	831.9	77.1	44.5	191.6	640.2	1023.5
Phase 3	781.4	761.4	846	796.3	44.2	25.5	109.8	686.4	906.1
SFC (g/l)									
Phase 1	0.14	0.15	0.14	0.14	0.0	0.0	0.0	0.13	0.15
Phase 2	0.10	0.08	0.08	0.09	0.0	0.0	0.0	0.06	0.11
Phase 3	0.08	0.05	0.13	0.09	0.0	0.0	0.1	0.00	0.19

The same analysis was completed for the runs using the oven and other performance indicators shown. Each uncertainty is reported alongside the value in Chapter 5.

Lastly, the uncertainty during the experimental sequences was determined by the standard deviation and the 95% confidence interval between three repeat runs and is reported as such in Chapter 4. The 95% is chosen to ensure that the parameter lies within the interval, increasing the confidence. Table E-5 shows an extract of the complete uncertainty analysis for the four species. The average and 95% confidence intervals are shown. The variation seen is deemed acceptable, due to the heterogeneity of raw wood cuttings. Lower repeatability is typically observed from wood combustion, due to the complexity and non-homogeneity of wood and its combustion processes (L'Orange, DeFoort, *et al.*, 2012). END